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GUIDE TO THE STUDY OF

NON-METALLIC MINERAL PRODUCTS

(*Except Building Stones*)

BY

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PREFACE

The purpose of this book is to furnish a basis for a one semester course in the study of the origin and occurrence of the more important non-metallic mineral substances that are employed in the industries. It is not intended to cover the subject in a comprehensive way. To do so would require a volume many times larger than this one. It is hoped, however, to familiarize the student with the principal sources to which he may go for further information. The conclusions presented as to the origin and distribution of the materials treated are not fully discussed; but references are given to the arguments upon which these conclusions are based. Nor is there any description of the minerals or rocks that are dealt with, nor of the geological processes to which they owe their existence. It is assumed that the student who uses the book will have some familiarity with mineralogy and geology.

The articles to which reference is made are not always the best ones to which the reader might have been directed. They are, however, authoritative, are written in English and are easily accessible in most libraries. Nearly all of them are by active workers who have actually seen in the field the phenomena discussed by them. They are the kind of articles that furnish the material upon which text books are founded. It is hoped that the student will be required to read most of them, if for no other reason than to become acquainted with the series of publications to which he must turn in future years, if he wishes to learn what is known about the origin and manner of occurrence of any non-metallic mineral substance in which he is

interested. It is hoped that he will be impressed with the fact that text books cannot be depended upon to furnish him with all the information he needs, and that for authoritative information he must go to the sources.

The illustrations are comparatively few. They are used to amplify the text and not to embellish it. They have been collected from many sources, chief among them being the publications of the Federal and State geological surveys. Many of the cuts have been furnished by the U. S. Geological Survey, by Messrs. John Wiley & Sons and by the McGraw-Hill Book Company, for which the author feels under many obligations.

Thanks are due to Prof. E. C. Jeffrey of Harvard University, to Messrs. Wallace E. Pratt, D. C. Barton, W. C. Spooner, V. L. Eardley-Wilmot, to President C. C. O'Harra, to the Pan-American Petroleum and Transportation Company, to the Barber Asphalt Company, to the State Geologists of Georgia and Tennessee and to the Mines Branch of the Canadian Department of Mines for supplying photographs from which illustrations have been made. Acknowledgments are also due Mr. V. R. Garfias, Prof. W. H. Emmons and Prof. H. G. Turner, who graciously permitted the use of illustrations that have appeared in their publications. The author appreciates their help and acknowledges it in the titles of the illustrations.

To Dr. W. V. Howard of the University of Illinois the writer wishes to express his hearty appreciation of the help generously granted him in the preparation of the chapter on Petroleum, and of the painstaking care with which he has read and corrected the proof of the entire volume.

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CHAPTER I

INTRODUCTION

The terms "Applied Geology," and "Economic Geology" are frequently regarded as synonymous. The former, however, has a broader significance. Both deal with the application of the truths and theories of geology to the solution of economic problems, but "Economic Geology," deals more particularly with theories than with practice. It is at present generally understood to be that phase of applied geology that deals with the more purely scientific aspects of the subject, while that phase which deals more particularly with the application of geological principles to practical problems is known as Engineering Geology. The Economic Geologist studies the distribution, nature, associations and origin of geological materials; the Geological Engineer deals with the problems relating to the handling of geologic materials for the benefit of mankind. The Mining Engineer is a Geological Engineer who devotes himself to the winning of geologic materials by mining methods.

Clearly the Geological Engineer and the Mining Engineer should have some knowledge of economic geology if they are to plan wisely for the future. The most noted Mining Engineers are at the same time Economic Geologists, but many of them are so busy with the strictly engineering side of their profession that they are unable to keep abreast of the progress of economic geology and consequently are compelled from time to time to call to their aid specialists to help them solve their problems.

All engineers dealing with geological matters should be

at least familiar enough with the fundamentals of economic geology to enable them to judge as to the necessity of seeking aid from specialists, and more particularly to weigh the value of the conclusions furnished them by those called in to help them solve their problems.

Economic Geology as it has been defined above deals with the application of geologic teachings to the study of the nature, distribution and origin of geologic materials that may find practical uses in manufactures and the arts. Incidentally it is concerned also with the production of the materials considered because the volume in which they may be produced and the cost of their production is a measure of their value.

In recent years interest has been directed toward the international distribution of the more essential products, since, by a more reasonable exchange of mineral commodities than has heretofore been practiced, civilization will be more rapidly advanced and the comfort and welfare of humanity will be bettered.[1] Moreover, with the rapid improvement in the means of transportation between distant parts of the Earth, the nations are becoming more and more mutually dependent. International politics is forcing its way to the front, and before many years diplomacy will busy itself with the most economical methods of exchanging raw products. It behooves the Economic Geologist to be ready to advise as to the cheapest sources of mineral materials, that the exchange may be beneficial to all parties concerned.[2]

For practical reasons it is convenient to divide the study of Economic Geology into two parts.

[1] G. O. Smith, "The Economic Limits to Domestic Independence in Minerals," U. S. Geol. Sur., *Min. Res.*, 1917, Pt. 1, pp. 1a–6a, 1921. C. K. Leith, "International Control of Minerals," *Ibid.*, Pt. 1, pp. 7a–16a, 1921.

[2] Cf. also, Leith, C. K., *The Economic Aspects of Geology*. New York, 1921.

I. The study of non-metallic substances.

II. The study of metallic substances, or rather of the sources of metallic substances, more generally known as ores.

Of the two classes of substances the ores furnish the most interesting and the most difficult subjects of study, but the non-metallic substances are the most important—if measured by money value.

In 1926 the United States produced of non-metallic substances a valuation estimated by the United States Geological Survey at $4,852,000,000, and of metallic substances a valuation of $1,402,920,000.[3] In both cases the valuation is calculated on the basis of the crudest product of each resource that enters the market. Thus the value of iron ore is calculated on the basis of the pig iron manufactured from it; of clay on the basis of pottery, etc.; of barite on the basis of crude and purified barite; of quartz on the basis of the crushed material; of rock on the basis of the quarry product, whether crushed, cut, made into building or paving blocks, etc.; of limestones on the basis of crude crushed limestone, building blocks, lime, cement, etc.

These estimates are faulty in that in many cases the cost of the labor employed in preparing the material for the market is greater than the cost of the raw material that is fashioned into the marketable product, but when it is realized that in most cases the raw material is valueless until it is fabricated, this method of evaluation becomes reasonable. Moreover, for purposes of comparison with the products of the field and forest, it is fairer than would be the case if all the cost of labor in the preparation for market were excluded, because in the valuation of the products of field and forest the cost of labor is necessarily included. Our lumber industry is valued

[3] And in addition about $7,000,000 worth of unspecified material of which about $6,000,000 represented non-metallic substances.

in terms of sawed lumber and not in terms of standing trees, or of logs lying in the forest, etc., and our agricultural industry in terms of crops grown, gathered and in many cases thrashed and cured. It is probable that a greater proportionate labor cost is included in the evaluation of non-metallic than of metallic products, but even if this be true, nevertheless, after all adjustments for this element are made, the annual world value of the non-metallic products would probably exceed that of the metallic products.

CHAPTER II

CLASSIFICATION OF THE NON-METALLIC SUBSTANCES OCCURRING IN THE EARTH'S CRUST

The non-metallic mineral products are the results of many different geological processes. Some of them exist as solids and must be mined or quarried, as, for instance, limestone. Some occur as liquids, or as mixtures of liquids and gases and are used as found. Water and petroleum are of this class. Others exist in solutions from which they are obtained by chemical processes or by evaporation, such as sodium carbonate in brines. Others occur in mixtures of gases, from which they are separated and made into commercial products by more or less complicated chemical or physical processes, like the helium which is extracted from the gas produced by some oil wells. The atmosphere is not commonly regarded as a mineral product, although there is no fundamental reason why it should not also be so considered, since it is now the source of the nitrogen which enters so largely into the manufacture of ammonia and nitrates.

The non-metallic mineral substances of commercial importance may be grouped as follows:

1. Those that occur as liquids or as mixtures of liquids and gases
2. Those occurring in aqueous solutions
3. Those precipitated from aqueous solutions
   (a) by evaporation
   (b) by supersaturation
   (c) by chemical reactions
   (d) through the agency of organisms

4. Those precipitated from igneous magmas
   (a) direct deposits from magmas
   (b) deposits from volcanic gases
   (c) deposits in pegmatites and igneous veins
5. Weathering products
   (a) residual deposits
   (b) secondary vein deposits
   (c) mechanical deposits
      1. fragmental sediments
      2. terrestrial fragmental deposits
6. Metamorphic deposits
   (a) those made by contact metamorphism
   (b) those made by dynamic metamorphism
   (c) those formed by hydration

It must not be understood that all products belong exclusively to a single group. Some of the commonest products belong at the same time in several groups. For instance, coal originated as a mass of vegetable debris, but this debris suffered much alteration before it became coal, and the different varieties of coal suffered different degrees of alteration as the result of metamorphic processes. Anhydrite is a precipitate from solution. When it becomes hydrated it changes to gypsum. The gypsum is a metamorphic product but it may inherit from the anhydrite the characteristic form of a bedded deposit.

MINERAL SUBSTANCES OCCURRING AS LIQUIDS OR AS MIXTURES OF LIQUIDS AND GASES

The only mineral substances that exist as liquids and that are used in this state are water and petroleum. Other liquids than these occur in the earth's crust, but they are solutions of materials that generally enter the trade as solids. Some of these solutions are marketed, but mainly as the sources of substances that reach their consumers as elements, such as bromine, or as compounds, such as halite (common salt).

Petroleum is a mixture of gases, liquids and solids. Some of the gases and most of the solids are dissolved in the liquids. Under favorable conditions the gases separate from the liquids and are sold as gas. Some of the crude liquid with its dissolved solids is sold in its natural condition, but most of it is refined by distillation; the fractional distillates entering the trade as the liquids gasoline, kerosene, etc., and the solids remaining as residues from which paraffin and asphalt are separated.

At many places the structure of the crust is such that great quantities of gas that have separated from the petroleum underground are trapped and held until their reservoirs are penetrated, when the gas escapes from the rocks and is caught in tanks and distributed through pipes as fuel.

Natural gas and helium are the only gases that are obtained from the rocks in sufficient quantity to be of commercial value, although in a few places escaping volcanic gases are made to yield valuable products, (see p. 21), and nitrogen is separated from the air to make nitrogenous compounds.

MINERAL SUBSTANCES OCCURRING IN AQUEOUS SOLUTIONS

Many substances of commercial importance are found as solutions in the water of the ocean and of certain lakes, in brines buried with sedimentary rocks, and in the circulating ground water. Some solutions are so rich in valuable constituents that they are used as the sources of commercial products which are extracted from them by artificial evaporation or by some simple chemical process.

MINERAL SUBSTANCES PRECIPITATED FROM AQUEOUS SOLUTIONS

Most of the substances that occur in solutions are found also as solids that have been thrown out of solution by

evaporation, by chemical reactions with other solutions, or through the agency of organisms. A few others have been formed by the chemical reactions of their solutions upon solids with which they may have come in contact, as, for instance, with minerals in the rocks through which the solutions may be travelling.

Among the most important of these substances are common salt (NaCl), sodium sulphate, sodium carbonate, calcium sulphate, calcium chloride, sodium nitrate, potassium nitrate and certain bromides and iodides. Some of the compounds enter the trade in their original forms, but others are sold as sources from which more valuable marketable products are obtained. The bromides, for instance, enter trade mainly as bromine.

(*a*) Precipitation by evaporation.—The largest source of many of the salts known collectively as salines is the water of modern and ancient seas, and lakes, and the principal process by which they are separated from their solution is evaporation.

The water of the open ocean contains 3.5% of solid matter, or its average salinity is 35 per mille., or 35 grams per liter. Enclosed bays or seas may be more or less saline than this, depending upon the relation existing between the supply of fresh water contributed to them by streams and melting ice and the loss of water by evaporation. Thus the surface water of the Arctic Ocean contains 25.5 grams of salts per liter, the surface water of the Black Sea, 18.3 grams, the water of the Baltic Sea at its junction with the North Sea, 34.2 grams, that of the Mediterranean Sea, 38.4 grams and that of the Red Sea, 38.8 grams.

The total salt content of the ocean and its bays, if extracted from the water, would bulk 5,100,000 cu. meters, and if spread over the entire sea bottom would make a layer about 60 meters thick. This, if separated into its

component parts (on the assumption that the named components would form) would consist of:

47.5 meters of common salt
5.8 meters of magnesium chloride
3.9 meters of magnesium sulphate
2.3 meters of calcium sulphate
.6 meters of other compounds

The constituents of the average sea water are present in quantities that would make the compounds named in the following list in the amounts indicated.

TABLE I.—SALTS IN THE WATER OF THE OCEAN

	Per Cent of Total Contents	*Grams per Liter*	*Tons per Cu. Mile of Water*
$NaCl$	77.758	27.213	131,526,080
$MgCl_2$	10.878	3.807	18,399,360
$MgSO_4$	4.737	1.658	8,012,480
$CaSO_4$	3.600	1.260	6,089,440
K_2SO_4	2.465	.863	4,169,760
$MgBr_2$	.345	.123	583,520
$CaCO_3$, etc	.217	.076	367,520

These compounds are, however, not necessarily produced when their solution is evaporated, for, as is now well known, salts are not present in solutions as such, but their component parts are present as ions. Combination of the ions into permanent salts takes place only as the latter are being thrown out of solution, and the nature of the salts thus produced varies with the conditions under which separation from the solvent occurs.

In the case of sea water, as in the case of other mixed solutions, different series of salts are precipitated as the conditions under which the precipitation takes place are changed.

When sea water from the Mediterranean was concentrated at room temperature Usiglio obtained the following results:

TABLE II.—SALTS PRECIPITATED DURING CONCENTRATION OF SEA WATER

Vol. of Solution	Fe_2O_3	$CaCO_4$	Gypsum	NaCl	$MgSO_4$	$MgCl_2$	NaBr	KCl
1.000								
.533	.003	.0642						
.316		Tr.						
.245		Tr.						
.190		.0530	.5600					
.1445			.5620					
.131			.1840					
.112			.1600					
.095			.0508	3.2614	.0040	.0078		
.064			.1476	9.6500	.0130	.0356		
.039			.0700	7.8960	.0262	.0434	.0728	
.0302			.0144	2.6240	.0174	.0150	.0358	
.023				2.2720	.0254	.0240	.0518	
.0162				1.4040	.5382	.0274	.0620	
Salts Separated	.0030	.1172	1.7488	27.1074	.6242	.1532	.2224	
Salts in Mother-liquor				2.5885	1.8545	3.1640	.3300	.5339
TOTAL	.0030	.1172	1.7488	29.6959	2.4787	3.3172	.5524	.5339

But varied results were obtained when the mother-liquor, or bittern, was allowed to evaporate slowly, slight changes of temperature being sufficient to produce marked differences in the products.

The order of deposition at room temperature during successive nights and days was:

1. Night. Epsomite ($MgSO_4.7H_2O$).
2. Day. Hexahydrate ($MgSO_4.6H_2O$), halite (NaCl) and a little sylvite (KCl).
3. Night. Epsomite.
4. Day. Hexahydrate, halite, schönite ($MgSO_4.K_2SO_4.6H_2O$), bischofite ($MgCl_2.6H_2O$) and $MgBr_2$.

5. Afternoon. Carnallite ($MgCl_2.KCl.6H_2O$).
6. Night. Carnallite and schönite.
7. Day. Nothing.
8. Afternoon. Carnallite.
9. Night. Carnallite and epsomite.
10. Autumn temp. 5°–6°. Bischofite.

Moreover, a solution does not necessarily always crystallize in the same way, yielding the same salts in the same order. Under the varying conditions that obtain during the concentration of a complex solution, reactions between the components may take place and very different results may ensue, depending upon the temperatures and pressures at which the separation of the salts takes place.

Van't Hoff has studied the effects of solutes upon one another. He showed that when *two salts with a common ion* are dissolved in a solvent the amount of each that will saturate the solution is less than if either were present alone.

Thus, in 1,000 mols. of H_2O at 25° C., saturation is produced by 111 mols. of NaCl or 88 mols. of KCl, but when both are present the solvent will hold in solution only 89 mols. of NaCl and only 39 mols. of KCl. Consequently, if a given solution of these salts contains more than 89 mols. of NaCl to 39 mols. of KCl, NaCl will separate on concentration until the excess has been removed, when both will separate together and the composition of the liquid will thereafter remain constant.

Hence; if a salt is present in a solvent to saturation and a second salt with an ion similar to one of those in the first salt is introduced into the same solution, a precipitation of the first salt will take place, and this will continue to separate with increasing concentration of the solution until a point is reached where both will separate together.[1]

Van't Hoff also investigated the separation of salts from

[1] See Grabau, A. W., *Principles of Salt Deposition*, p. 67. McGraw-Hill Book Co., New York, 1920.

sea water under different conditions and found that when evaporated at 25° C. carnallite, schönite, glaserite ((K. Na) SO_4), kainite, leonite ($K_2SO_4.MgSO_4.4H_2O$), and astrakanite ($Na_2SO_4.MgSO_4.4H_2O$), are formed, and when evaporated at 83° langbeinite ($K_2SO_4.2MgSO_4$), loeweite ($2Na_2SO_4.2MgSO_4.5H_2O$) and vanthoffite ($3Na_2SO_4.MgSO_4$) separate.

Moreover, if sea water is condensed until it is saturated for NaCl and then is evaporated at 25° C. the compounds and the proportions of each that separate in four different stages are:

Table III.—Order and Proportions of Salts That Separate from Sea Water Saturated with NaCl, and Evaporated at 25° C.

	Rock Salt (NaCl)	*Kieserite* ($MgSO_4.H_2O$)	*Kainite* ($MgSO_4.KCl.3H_2O$)	*Carnallite* ($MgCl_2.KCl.6H_2O$)	*Bischofite* ($MgCl_2.6H_2O$)
1.	95.4				
2.	4.42	1.05	2.02		
3.	.03	.35		.10	
4.	.15	.38		.08	7.62

If, however, the condensed sea water is evaporated at 83° C., the order of formation of the minerals separated is: rock salt, loeweite, kieserite, carnallite and bischofite, in each case with halite (NaCl).

(*b*) Precipitation by supersaturation.—Precipitation from solution may also take place by supersaturation, if several substances containing the same elements exist and one form is more soluble than the others. The least soluble compound will be thrown out of the solution as the more soluble one is dissolved.

The maximum solubility of $CaCO_3$ in sea water is 0.191 grams per liter. Since organic $CaCO_3$ is more soluble in sea water than is the crystalline salt that is not the direct

result of life processes, supersaturation may take place with respect to the crystalline form of $CaCO_3$ in the vicinity of coral reefs, and calcite may be deposited in temperate water and aragonite in warm water. Thus shells or broken coral are cemented into rocks like the coquina of Florida, and limestones are produced.

Supersaturation takes place about the mouths of some rivers off some limestone coasts, and at the orifices of some springs, where there is a large content of calcium bicarbonate in the water. With the escape of the carbon-dioxide, due to evaporation, the bicarbonate is changed to the carbonate, which is much less soluble than the bicarbonate and is precipitated whenever more of it is made than the water can hold in solution.

(*c*) Precipitation by chemical reaction.—Another cause of precipitation from solution is chemical reaction between substances already in the solution and others introduced into it.

Thus putrefying organic matter in the sea or lakes produces ammonium carbonate which may react with $CaSO_4$ and $CaCl_2$ that may be present and transform them into $CaCO_3$, which is insoluble and will precipitate as calcite or aragonite in more or less spherulitic forms. In the ocean little organic matter decays, but in the Black Sea, where scavengers are scarce, thin beds of fine-grained limestone are being deposited by this process.

(*d*) Precipitation through the direct agency of organisms.—Among the most important causes of the separation of salts from their solutions are the life processes of animals and plants.

Some bacteria, as stated above, generate ammonium carbonate which serves as a precipitant of calcium carbonate from sea water. Some plants extract carbon-dioxide from the water surrounding them and in this way cause the precipitation of aragonite.

Algæ, corals, foraminifera, sponges, bryozoans, brachiopods, molluscs, crustaceans, echinoderms and worms secrete $CaCO_3$ as external coverings and on their deaths give rise to accumulations of calcite, travertine, chalk or other forms of limestone.

Most plants absorb dilute solutions through their roots, transpire the water or use it in building sap or tissue, leaving the salts in their cells, often as minute crystals. These may be recovered by burning the organic matter and leaching the ashes left unconsumed. Some potash and iodides are produced in this way.

The sulphur bacteria decompose H_2S, or reduce sulphates and store sulphur in their cell-protoplasm. Upon the death of the organisms beds of sulphur may result.

DEPOSITS FROM MAGMAS

Among the most important sources of non-metallic deposits are the magmas which upon cooling yield lavas and other igneous rocks. Magmas are liquids at high temperature that consist of solutions of complex silicates and perhaps admixed oxides, and contain dissolved materials that are volatile at temperatures lower than the temperature of their solvent. The primary products from magmas result (1) from their cooling, by which certain substances crystallize directly from the molten mass, (2) from the cooling of the hot vapors which are given off during the solidification of the magmas, and the precipitation of some of their constituents during their rise to the surface, and (3) by precipitation from the cooling gases and solutions that escape when the magmas approach the surface. (Fumarole deposits.)

DIRECT DEPOSITS FROM MAGMAS

The non-metallic economic substances that separate directly from magmas as the result of cooling, possibly of

changes in pressure, and of variations in concentration, due to changes in composition resulting from differentiation, are few. Many of the rocks are of this class but they are of value not because of their composition, but mainly because of their physical properties. Other substances, aside from metallic compounds, which are direct separations from igneous magmas are diamonds, corundum, garnet, and olivine. Pyrite and monazite are also precipitated from magmas, but they are both more common as separations from the solutions that form veins and pegmatites.

DEPOSITS FROM VOLCANIC GASES

The gases that escape from lavas are well represented by the emanations from the fumaroles of Kilauea and Mt. Pelée.

TABLE IV.—COMPOSITION OF VOLCANIC GASES[2]

	Kilauea	*Mt. Pelée*
CO_2	62.3	15.38
CO	3.5	1.60
CH_4	....	5.46
H_2	7.5	8.12
O_2	....	13.67
N_2	13.8	54.94
A	....	.71
SO_2	12.8	....
HCl	....	Tr.
S	....	Tr.

A recent study[3] of five specimens of the lavas of Mt. Pelée has shown that in these lavas there are from 4.3 c.c. to 26.5 c.c. of gases measured at 1,200° C. and 760 mm.

[2] For analyses of volcanic gases and a description of their sublimates, see Clarke, F. W., "Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 255–268, 1924.

[3] Shepherd, E. C. and Merwin, H. E., "Gases of the Mt. Pelée lavas of 1902," *Jour. of Geol.*, Vol. 35, pp. 97–116, 1927.

These are believed to be the residues of gases that were trapped in the congealing magma, before they had an opportunity to escape.

Two analyses gave the following results:

TABLE V.—VOLUME PERCENTAGES OF TOTAL VOLUME OF GAS AT 1,200° C., 760 mm. IN MT. PELÉE LAVAS

	Pumice	*Glass*
CO_2	7.441	0.824
CO	1.256	0.214
H_2	0.435	0.427
N	2.371	0.213
A	0.007	Tr.
SO_2	Und.	0.010
S_2	2.892	0.053
Cl_2	10.495	0.991
F_2	4.289	1.038
H_2O	70.812	96.227
TOTAL	99.998	99.997
C.c. of gas per gm. of rock	5.9	26.5

All known magmas contain the constituents of water. As the magmas cool, or approach the surface, where the pressure is less than at depths, water, with other volatile components of the magmas, separates from the molten masses and rises. When a magma reaches the surface as lava, much of the water escapes as great clouds of steam. Some portion, however, is trapped by the magma as it solidifies to rock. Rocks, like obsidian and other glasses, that cooled quickly retain a comparatively large portion of their dissolved water. Others, like granite, which cooled slowly, retain a smaller portion. However, the quantity that was retained is so large that we must infer that the portion that escaped was enormous. The amount of water in the average igneous rock in the earth's crust is

estimated by Clarke[4] to be 1.15% of its mass. A loss of less than 2% of this would furnish as much water as is in all the oceans.

Besides the constituents of water, there are included in the gases of many volcanoes small quantities of the vapors of various volatile substances which deposit when the temperature of the gases falls. Deposits of sulphur and of chlorides are common around many fumaroles. One of the sublimates around a vent of Hecla contained 81.68% of NH_4Cl. Around a fumarole of Vulcano are deposits of boric acid, around other fumaroles, realgar, ferric chloride and various sodium salts that are made by the action of the gases on the surrounding rocks.

Boron compounds are found in abundance in the lagoons formed by the condensation of vapors from the fumaroles in Tuscany, Italy. Ammonium sulphate and boric acid (H_3BO_3) are the chief vapors that escape with the steam. These dissolve in the water and are later precipitated mainly as sassolite (H_3BO_3) and borocalcite ($CaB_4O_7.4H_2O$).

Borax is deposited around hot springs in Cashmere, North India, often forming cones rising 15 or 20 feet above the surrounding borax-covered plain, and the same mineral is found in the extruded mud of mud volcanoes near the Sea of Azov.

Boron salts are also in process of deposition at the hot springs of Bonos del Toro at Coquimbo, Chile, and are found in the solares of Argentina where their presence is ascribed to the geysers and hot springs that are the last gasps of the volcanic activity of the region.

There are no commercial products that are now being obtained from the deposits of modern fumaroles, except sulphur and borax. At times, however, attempts have

[4] Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, 1924, p. 29.

been made to condense the volcanic gases and obtain from them their other valuable components, but these attempts have not proven successful because of the difficulty of controlling the pressures. In Italy, however, the hot gases of some fumaroles are utilized to produce power, and in the process some products may be saved.

DEPOSITS IN PEGMATITES AND IGNEOUS VEINS

Though deposits of economic importance are rare around fumaroles, the vapors and gases from magmas, as they make their way to the surface, may deposit many compounds in their conduits, and some of these are of great value.[5] Among them are many of the metallic compounds and a few non-metallic substances that occur in veins.

PEGMATITE VEINS.—Pegmatite veins, or dikes, are vein-like or dike-like aggregates of silicates and other rock constituents that are believed to be deposits from the mother liquors squeezed from cooling magmas during the progress of their solidification. The liquids are portions of the magma holding in solution large amounts of gases and vapors. The veins are filled by the material solidifying from these igneo-fluid emanations as they approach the surface and are cooled and relieved of pressure. The least volatile and least soluble substances precipitate first, later those more volatile and more soluble and finally the most volatile and most soluble. As some quartz veins are followed backward toward their sources they are found to pass gradually into coarse aggregates, composed mainly of quartz and feldspar, or of these minerals and mica, hornblende, or other ferro-magnesian compound. These coarse-grained aggregates are pegmatites.

[5] Kemp, J. F., "The Rôle of Igneous Rocks in the Formation of Veins," Am. Inst. Min. Engrs. *Trans.*, Vol. 31, pp. 169–198, 1902, and *The Genesis of Ore Deposits*, pp. 681–809, 1902.

Pegmatites may have a varied composition, depending upon the character of the magma that gave them birth. Pegmatites corresponding to all the common rocks are known, but the most important from an economic point of view are the granitic pegmatites.

As the pegmatites are among the last products of a cooling magma they may represent that portion which is left after many of its components have crystallized as rock constituents. They therefore contain in addition to their major components those substances that originally occurred in the magma in small quantities only. Many of these are sources of metals, but others are silicates, and among them are many of the minerals used as gems.

The non-metallic economic substances obtained from granite pegmatites are feldspar, quartz, mica, tourmaline, beryl, spodumene, amblygonite, topaz, apatite, monazite, zircon, and cryolite.

Igneous veins.—Veins filled by the emanations from cooling magmas are widely spread, but most of them are of interest because their contents are in part native metals, or compounds that are sources of metals. Some of them contain gangues of valuable non-metallic substances that are saved as by-products in the concentration of their metallic contents for use as ores. Others are filled only with non-metallic substances of which a few are of commercial importance. Igneous veins differ from pegmatite veins mainly in the nature of their contents. Both were formed by the same general processes. The pegmatites are essentially aggregates of ordinary rock-forming minerals, whereas, veins are composed of minerals, most of which are not found in rocks except in small amounts.

The student of ore veins distinguishes between those filled at great, moderate and shallow depths, because the character of the filling varies with the temperature and pressure at which the ore minerals separate from the

emanations. The distinction, however, is not so important when applied to veins filled only with non-metallic substances.

The principal non-metallic substances obtained from igneous veins are fluorite, quartz, alunite, apatite and barite.

WEATHERING PRODUCTS

When rock masses are acted upon by the atmosphere their soluble components, and compounds made soluble by decomposition, are dissolved and carried into lakes or the ocean where they remain to add to the salinity of the water until they are precipitated by chemical reaction with other constituents, by evaporation, or through the action of organisms. Their insoluble components and their insoluble weathering products may be left behind to form residual deposits, or they may be washed by the rivers into lakes or seas, falling to the bottom in response to gravity, unless kept in suspension by currents. A portion may be deposited in the channels or along the sides of the streams, a portion may be cast upon the shores of the lakes and seas and a third portion may cover their bottoms forming bedded deposits.

RESIDUAL DEPOSITS

Residual deposits are those left in the place where formed after the removal of other substances either by solution or by the action of running water. They occur either on surfaces with gentle slopes or in situations from which running water cannot sweep them away. Among the most important of the residual deposits are some kaolins, some clays, fuller's earth, tripolite, bauxite and some barite.

Deposits of economic value that were formed on the surface of the land by processes other than weathering are

very few. The most important are niter and soda niter. Both of these are deposited only on land and are probably produced by the action of nitrifying bacteria on decomposing material that is in contact with alkaline materials such as lime, wood ashes or the alkaline decomposition products of rocks. In moist regions the nitrates are carried off by the ground-water, but in arid regions or in protected places they may accumulate on the surface or in the soil. The niter of Chile and the saltpeter in many caves may have been made in this way.

SECONDARY VEIN DEPOSITS

Some veins were formed by the filling of cracks in the crust by precipitates from rising magmatic waters. (See p. 21.) Others originated by the filling of cracks by deposits from circulating meteoric waters, which gathered their burdens from the surrounding rocks, or their weathered products, and dropped them in consequence of chemical reactions between the solutions and rising gases, between the solutions and the wall rocks, or between solutions from different sources. Some barite, some zeolites, some calcite and a few less important substances may have this origin. The greater portion of such vein fillings are said to be secondary because formed directly from pre-existing minerals.

MECHANICAL DEPOSITS

Mechanical deposits of economic importance are sediments. They include those substances that have been dropped by water in which they have floated or have been held in suspension, those deposited by ice, those blown by the wind and those buried in the soil. They consist of accumulations of shells and internal skeletons of marine, lacustrine and fluviatile organisms, the shells

and bones of terrestrial animals and parts of plants that were buried in swamps or carried to the sea or lakes by streams; minerals or fragments of minerals that were washed from areas of decomposed rock and rolled along at the bottoms of water currents or swept along as suspended particles in moving waters until a slackening of currents caused them to be dropped; and mineral and rock particles worn from rock masses by moving ice and deposited upon its melting. Coquina, some phosphate rock, some kaolin, infusorial earth, quartz sand and all placers are deposits of this kind.

Fragmental sediments.—Most mechanical deposits are either sediments derived directly from weathered rock, or are fragments of organisms. They occur in beds and belong to the class of sedimentary rocks. Some of them remain in their original condition with very little change in composition (e.g., quartz sand), whereas others begin to suffer alteration as soon as formed, with the result that the final product is markedly different from the original deposit. The material of much limestone was originally a mass of shells and shell fragments. Since its deposition, however, the mass has been wholly or partially dissolved and some or all of the dissolved material has been subsequently precipitated with the result that the bed of limestone is very unlike the original accumulation.

Some gravel, sand, clay, some limestone, some phosphate rock and shales are fragmental sediments. Marine placers are also of this type.

Terrestrial fragmental deposits.—The masses of organisms and fragments of organisms, which, under favorable conditions, are spread over the land or are deposited in shallow depressions in its surface, may be covered and preserved. These may later become consolidated into rocks, with or without having been subjected to alteration, and may become of commercial value.

Dune sand, some forms of gypsite, stream placers and glacial moraines may be cited as illustrations of terrestrial deposits that have not been essentially changed since their deposition. On the other hand, coal was originally a deposit of vegetable debris in swamps or shallow lakes, but since its deposition this debris has been greatly changed in composition, appearance and properties and now is an entirely different substance of great value.

METAMORPHIC PRODUCTS

Many economically important compounds are the result of the alteration of previously existing substances which are themselves of little value.

Gypsum that is formed by the action of sulphuric acid on coral is a good example of a compound produced by the alteration of a previously existing substance of another kind. Water, leaching pyrite, becomes charged with sulphuric acid, which, acting upon the calcium carbonate of the coral, replaces the carbonic acid and changes the coral to a mass of crystallized gypsum. In the Salina of New York great irregular masses of gypsum are enclosed in limestone. The gypsum masses end below at a layer of impervious material and extend upward from this base into the limestone above, and impure shaly limestone layers that have not been altered extend unbrokenly through both limestone and gypsum. These afford the proof that the gypsum has replaced the purer limestone.

In some places, limestone beds above gypsum are broken and crumpled as though forced upward and sidewise by pressure which was apparently the result of the swelling of the gypsum. In this case it is believed that the gypsum was made by the hydration of anhydrite which is the common precipitate of $CaSO_4$ from solutions of high salinity.

All substances that are produced by weathering or by

contact and dynamic metamorphism are of the same general class, i.e., they are the products of alteration of other substances, but, since weathering processes usually result in hydration or in the breaking down of compact masses into less compact ones, whereas contact and dynamic metamorphism usually result in the opposite changes, weathering and metamorphism are generally considered separately, though contact metamorphism through the agency of magmatic fluids may also in some cases result in hydration.

The change of anhydrite ($CaSO_4$) to gypsum ($CaSO_4 \cdot 2H_2O$) is hydration by weathering, whereas the alteration of orthoclase ($KAlS_3O_8$) to kaolinite ($H_4Al_2Si_2O_9$), along the sides of some veins, is an illustration of hydration by the kind of contact metamorphism known as hydrothermal alteration.

Contact metamorphism.—Contact metamorphism is the change produced in the materials surrounding an igneous mass by the hot gases and vapors that are pressed out of it during the process of crystallization. A few gem minerals occur in limestone around igneous contacts, but most of the commercially important contact products are metallic. Kaolin and alunite were made in igneous rocks alongside some igneous veins, by reactions between the constituents of the rocks and solutions that were forced into them from the vein fissures.

In some places the solutions rose through tiny cracks in which there was no deposition. These solutions, however, passed into the wall rocks, reacted with the rock constituents and replaced them with new material on both sides of the cracks, thus producing a vein that differs from the filled igneous vein (p. 21) in that its material does not occupy a fissure. Veins of this kind are called "replacement veins." Some of the large veins of alunite and barite are replacement veins.

Dynamic metamorphism.—When deformation of the rocks in the earth's crust takes place there is movement of their parts with attendant heat and pressure. As a result certain reactions take place between the constituents present and often new arrangements of molecules occur and new minerals result. Some of these are of importance commercially, but others are produced in such small quantity that they are of little economic value.

Among the most important products of dynamic metamorphism are asbestos and talc, both of which are used in large quantity for a great variety of purposes, and kyanite and sillimanite that are rapidly coming into use as sources of alumina in the ceramic industry.

CHAPTER III

UNDERGROUND WATER

GENERAL STATEMENT

Among the mineral substances exploited by man are some that are utilized in their natural state with very little elaboration to make them more suitable for consumption. Among these the most important is water. This occurs on the earth's surface in the form of seas, rivers and lakes and beneath the surface as ground-water. Rivers and fresh-water lakes are employed directly as sources of water supply for domestic, manufacturing and other purposes. The ocean and many lakes, especially those in dry regions, furnish salts of various kinds.

The underground water, where fresh, is an important source of water especially in dry regions, and in regions where the surface water is contaminated with objectionable substances. In some places where underground water is impregnated with salts, it is a source of valuable compounds. The contributions of underground water in the way of salts are discussed in a later chapter. In this chapter attention is directed to the underground supply as a source of water.

THE GROUND WATER

Sources.—Most of the water that occurs on the earth's surface and that within easy reach beneath the surface was obtained from the rain. A portion was buried with the rocks in which it occurs and a part was furnished by cooling magmas or by rocks that are undergoing certain kinds of changes, known generally as metamorphism.

Meteoric water is that supplied by the rain, snow and fogs. The amount that falls varies greatly in different places. It is as much as 60.6 inches annually near the coast in Oregon, Washington and a few other portions of the United States and less than 5 inches [1] annually in western Nevada.

Some of the water that falls on the land runs off into rivers and lakes, another portion is evaporated and the remainder sinks into the ground.

The ratio between the rainfall and the run-off is fairly constant for any given region but varies widely in different regions, being dependent upon several factors among the most influential being:

1. The quantity and intensity of the precipitation.
2. The slope of the surface.
3. The character of the surface, i.e., whether bare, or soil-covered; dry or wet; porous or impervious; frozen or not. If bare, wet, or frozen the run-off is excessive, in some places equalling nearly all of the rainfall. Where soil-covered, dry and not frozen all the water that falls may be absorbed and there may be no run-off if the precipitation is gentle.
4. The character of the vegetable covering.[2]
5. The direction, strength and temperature of the winds, i.e., the rapidity of evaporation. On the Virginia Coastal Plain the evaporation equals about 50% of the rainfall, and the run-off is comparatively slight.

Only that portion of the rainfall that is absorbed reaches the underground reservoirs and becomes a part of the ground water. Excluding the portion of the rainfall that is evaporated, the part that is absorbed is roughly the complement of the run-off. The factors that increase the absorption tend to decrease the run-off.

[1] One inch of rainfall on a square mile of area equals 2,323,200 cu. ft. of water, about 17,000,000 gals. or 70,000 tons.

[2] Zon, R., "Forests and Water in the Light of Scientific Investigation," Nat. Waterways Com., 1912, *Final Rept.* Appendix V. Washington, 1927.

Connate water is that which is buried with the rocks containing it. The sedimentary rocks are laid down for the most part in the ocean or inland seas. When deposited they imprisoned water between their grains. Where such deposits were covered with impervious beds the water was sealed in the pores of the underlying rocks and was buried, then becoming fossil water.

From the composition of the water imprisoned in old sandstones, it is believed by some geologists that the composition of ancient oceans may be learned, and from the difference in the amounts of certain salts in these old brines and in the present ocean water the time that has elapsed since the rocks and brines were buried has been calculated.[3]

The connate water that was sealed off from the rest of the ground-water is an important source of salts. That which was not sealed off has become a part of the general ground-water layer. Some of it has been lost by drainage and some has been lost by evaporation after being drawn to the surface by capillarity.[4]

Magmatic water is that contributed by cooling magmas and by the resulting rocks. It has long been known that great volumes of water vapor escape from volcanic vents, from fumaroles and from cooling lava. Where magmas cool beneath the surface, much of the escaping vapor may mingle with the meteoric ground-water. Where conditions are favorable for crystallization, most of the water may be squeezed from the magma, but where the conditions for crystallization are unfavorable, the magma solidifies to glass in which much of the water is retained (p. 18). Some analyses of volcanic glasses show the presence of 5% of water. Even in the rocks composed of crystals there is a notable quantity of water, partly in the

[3] See Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 150–155, 1924.

[4] Lane, A. C., "Mine Waters and Their Field Assay," Geol. Soc. Am., *Bull.*, Vol. 19, pp. 501–512, 1909.

form of fluid inclusions and partly in the form of hydrous minerals, such as the micas. Clarke estimates the amount of "combined water" in the average igneous rock as 1.15%.

The "combined water" is not fluid water, but when freed from the mineral of which it is a component, either by heating, by solution, or by reactions whereby anhydrous minerals are formed, the "combined water" becomes fluid water. It is estimated that the combined water alone in the rocky part of the earth is sufficient to supply many times as much water as all that in the present oceans (p. 18). It is probable that if one could estimate the quantity of water in the minerals as "fluid inclusions" and that dissolved in molten magmas, it would be found that the aggregate amount of water that might be furnished by the rocks would be greatly increased.

The underground water is thus contributed to by meteoric, connate and magmatic water in various proportions. In some places the connate, or magmatic, water is believed to be in sufficient quantity to affect the composition of the underground layer, but in most places the meteoric water is in such great excess that it is practically uncontaminated.

That portion of the ground water contributed by the rain is known as *vadose* and that contributed by rocks and magmas as *juvenile*.

The ground water layer.—According to the views of most students the ground water is limited to a layer a few thousand feet thick, the upper surface of which, known as the "water table" or "ground water level," follows in general the contour of the ground, but with more gentle slopes. In arid regions its upper limit is some distance beneath the land surface, but in humid regions it is comparatively close to the land surface, and in some depressions is actually above it. (Fig. 1.) In the zone between the water table and the surface there is a nearly continuous

circulation of water downward during wet weather under the impulse of gravity and upward during dry periods as the result of capillarity. This is the vadose zone.

The ground water below the water table moves very slowly in rocks of uniform character. It nevertheless circulates and if there is an outlet at a lower level than the water table it will issue at the surface either as a spring, a seepage, or through a well opening.[5] As the country is eroded the water level sinks downward and within certain

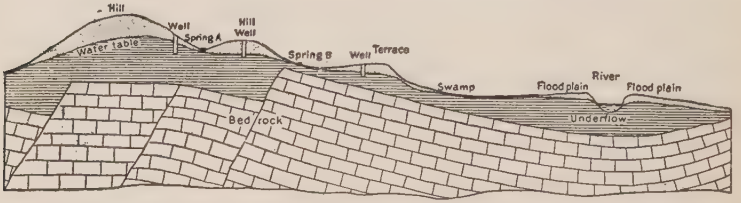


FIG. 1.—Figure showing relation of water table to surface irregularities. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

limits it changes with the season, sinking during dry periods and rising during wet ones. This difference in width of the zone above the water table is usually greater under hill tops than on slopes or in valleys.

The relation of the upper surface of the ground water layer to that of the land is of great significance in the discussion of the enrichment of ore bodies, since chemical reactions may occur in the zone above the water layer that are impossible in the water-saturated layer, because the pores of the rocks in the upper zone contain oxygen, whereas those of the rocks in the lower zone are filled with water.

Below the zone of the deeper circulation, which is limited below by the altitude of the points of escape, the rocks are saturated with water which must be nearly stagnant. The surface of division between the sluggish,

[5] Slichter, C. S., "The Motions of Underground Waters," U. S. Geol. Sur., *Water-Supply Paper*, 67, 1902.

deeper circulation and the zone of "static," or nearly stagnant, waters beneath it, is indefinite, except where the lower limit of the former is determined by layers of impervious rock. Where, in the rocks, there are structural features that afford inverted siphons to serve as water conduits there may be a considerable movement of water below the lowest outlet of the ground water, and where the conduit is tapped it may furnish water under pressure.

The depth of the lower limit of the ground water has been a subject of much discussion. As the water must be held in the pores between the grains of rocks it can exist only where there are such pores. Van Hise[6] estimates that pores can exist only to a depth of 6 miles, but Adams[7] has shown by experimental work that pores may exist in some rocks at pressures that are equivalent to a depth of 11 miles. Much of the water at the lower levels, however, cannot be free as it exists in capillary openings from which it will not flow readily. It is this fact that may explain the discrepancies in the views of Van Hise on the one hand and of many economic geologists on the other. Kemp and others have shown that deep mines are usually dry and that deep borings likewise show no water in their lower portions, except in rock layers that may serve as conduits. Since water is not visible unless it is free, it is possible that at great depths the water, if present, is held so tightly in tiny openings that it will not flow and for this reason is not visible on the walls in deep mines. If this water is not free to move it is not available for the purposes for which the ground water is utilized and therefore its discussion may for the present be omitted.

In some places a mass of water underground is raised

[6] Van Hise, C. R., "A Treatise on Metamorphism," U. S. Geol. Sur., *Mon.*, Vol. 47, p. 129, 1904.

[7] Adams, F. D., "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. of Geol.*, Vol. 20, pp. 97–118, 1912.

above the general water table and separated from it by a thickness of dry rocks. Such masses are known as perched water tables and are due to the presence of impervious layers which interrupt the vadose circulation. (Fig. 2.) A well may obtain water from a perched water supply some distance above the general water table, and lose it by passing through the underlying rock and entering an unsaturated zone above the general water level.

Quantity.—The quantity of ground water beneath the surface depends mainly upon the rainfall over the surface

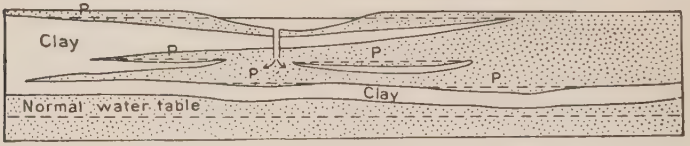


Fig. 2.—Section illustrating perched water tables. If P is an unsaturated zone above the general water level, a well may pass through a perched table and drain it. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 258.*)

and the porosity of the rocks in which it may be stored. Fuller[8] estimates that a mass of soil or loam contains 50% of pore space, a mass of sand 30%, of sandstone 15%, of shales 4%, of limestone 5%, of granite and quartzite 0.2%.

These figures indicate the capacity of a rock for absorbing water, but, according to Fuller, in stratified rocks only 37% of the pore space is occupied by water and in crystalline rocks about 50% of the pore space. This is the "free" water in the rocks. The "available" water is that portion of the free water that will flow to an opening or respond to a pump. A rock may contain much free water, but may hold it so tightly that it will yield only a meager amount to springs, wells or pumps.

On the basis of these estimates Fuller calculates that, as

[8] Fuller, M. L., "Total Amount of Free Water in the Earth's Crust," U. S. Geol. Sur., *Water-Supply Paper*, 160, pp. 61–72, 1906.

a rule, 5.25% of the volume of sandstone, 1.48% of the volume of shales, 1.75% of the volume of limestone, and 0.1% of the volume of crystalline rocks is free water.

On the assumption that sedimentary rocks throughout their entire thickness, i.e., to a depth of 2,600 feet, which is their average thickness over the entire globe, and crystalline rocks to a depth of 15,375 feet, are capable of holding water, there is free water in the earth's crust equivalent to a uniform sheet over its entire surface with a depth of 96 feet, or a quantity equal to one-hundredth of the volume of the ocean. Slichter[9] computed the amount of ground water in the crust to be equal to an envelope of from 3,000 to 3,500 feet in thickness and Van Hise[10] to one 226 feet thick over the continental areas.

About the only safe generalization that can be made with reference to the quantity of ground water is that in crystalline rocks the presence of available water is limited to joints and other structural crevices within 600 feet of the surface. Therefore a well in crystalline rocks that does not reach water within a few hundred feet of the surface is not likely to furnish supplies at any greater depth. In sedimentary rocks the depths to which the ground water extends varies with the texture of the rocks, the degree to which they are shattered, the depths to which they are cut by streams, etc., their structure and the presence or absence of interlayered impervious beds.

SHALLOW WELLS AND SPRINGS

Definitions.—Wells are artificial openings into the water table. Common wells tap perched water tables or the upper layers of the ground water. They are the usual

[9] Slichter, C. S., "Motions of Underground Waters," U. S. Geol Sur., *Water-Supply Paper*, 67, p. 14, 1902.

[10] Van Hise, C. R., "A Treatise on Metamorphism," U. S. Geol. Sur., *Mon.*, Vol. 47, pp. 128–129, 570–571, 1904.

wells employed to furnish water for domestic purposes, delivering it under very slight pressure or none. The rise and fall of the water level in common wells is due almost exclusively to rise and fall of the ground water level in their neighborhood. Technically they are known as shallow wells.

Deep wells are wells bored into the ground water to secure supplies from sources at a greater depth than that of the surface layers. They usually deliver their water under a head which causes it to rise in the opening, in some cases even to a considerable height above the mouth of the well. Those delivering water above the land surface are called "flowing" wells.

Artesian wells are those that tap water in conduits, e.g., water that is enclosed in porous beds between impervious layers or that is entrapped in some other way. The artesian wells nearly always deliver their supplies under head. Springs are flows of the ground water through natural openings to the surface.

Shallow wells.—The water of shallow wells, as a rule, has the same composition over wide areas. Its character is determined largely by the nature of the rock occurring immediately beneath the surface. That obtained in limestone regions is "hard," whereas that in regions where the underlying rocks are non-calcareous is usually soft.

Under very special conditions well water may be impregnated with mineral matter other than calcium or magnesium salts, when it is known as "mineral water." One of the most common impregnations is iron carbonate, producing a "chalybeate water," another is sulphuretted hydrogen, yielding a "sulphur water." The sulphuretted hydrogen in most cases is due to the decomposition of organic matter, in which case the water may be contaminated with sewage, and may be dangerous for human consumption. Since ordinary wells penetrate only a short

distance beneath the upper level of ground water, their supplies are obtained from near the surface, where there is an intermingling of the surface water with the general supply of ground water. If the surface water drains cesspools, cultivated lands, or villages it may contain objectionable impurities, which will be drawn into the wells to the injury of the well water (Fig. 3).

Before well water is utilized for any purpose the surroundings of the well should be carefully investigated to

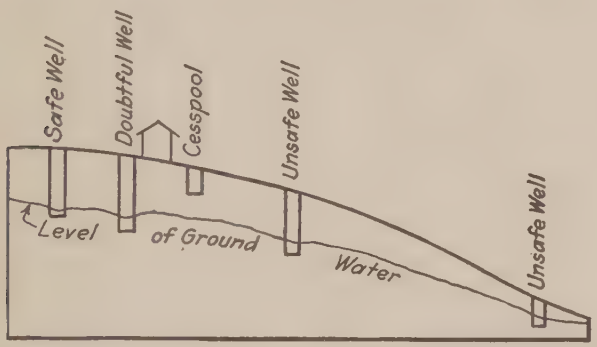


FIG. 3.—Diagram showing relative positions of safe, doubtful and unsafe shallow wells. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

make sure that surface water may not have entered it either directly or through the soil. The rock exposures in the vicinity of the well should be examined, and the character and the direction of dip of the rock should be noted. Wells in limestone are more dangerous than those in other rocks or in unconsolidated materials, because, whereas in the latter the water is partly filtered, in the former it frequently flows in channels, thus escaping filtration. Since water travels much more readily down the dip of bedded layers than across them, the existence of rocks dipping toward the well from cesspools or barns is apt to result in serious contamination of the well water. Moreover, a

well in jointed rock is to be looked upon with suspicion since the drainage of outhouses may enter the well directly by passage through the joint fissures.[11] (See Fig. 4.)

Springs.—Springs issue through natural openings into the ground water supply. They may be temporary, permanent or intermittent, depending upon the shape of the crevice and the depth to which it reaches. Because spring crevices are outlets from various portions of the ground water they may deliver water of varying temperatures and compositions.

Character of water.—Over wide areas the water of springs may be "hard" or "soft," and its degree of hardness will

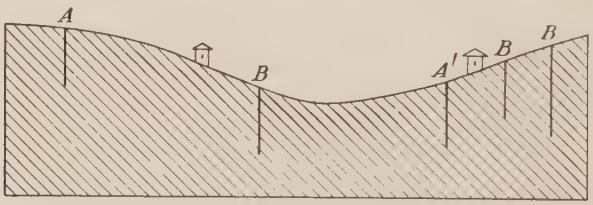


Fig. 4.—Diagram illustrating the influence of the dip of rocks upon the quality of the water supplied to wells. A is a safe well: A′ is safe if protected at surface. Wells marked B are unsafe.

be approximately the same in the case of all springs draining an area under which the geological conditions are uniform.

Many springs, however, have conduits through insoluble rocks that reach the stores of ground water below the depths at which there may be a commingling with large quantities of surface water. Such springs deliver comparatively pure water, free from objectionable constituents. Other springs flow through soluble rocks which are partially dissolved by the rising water, or their conduits tap the upper surface of the water table and deliver water that is a mixture of the ground water with surface water,

[11] Cf. Fuller, M. L., "Underground Waters for Farm Use," U. S. Geol. Sur., *Water-Supply Paper*, 255, 1910.

or their conduits pass near hot masses of rock causing their contents to be heated, or, finally, their channels may extend downward into regions where cooling magmas are giving off magmatic water, and a large part of the delivered water may be of this origin.

Spring water is employed mainly for domestic purposes. It is, for some reason, commonly supposed that spring water is purer than well water. While it is true that much of the water that issues from springs is more desirable as a table water than the water of many wells, the popularity of spring water is due mainly to advertising. Locally springs may furnish cooler or more pleasant tasting water than that of wells, but as a rule the water of a properly located and carefully protected well should be as wholesome as that of a spring in the same neighborhood.

The most desirable water for general use is cool, free from excessive mineral content and from an excess of sulphur gases, carbon dioxide and chlorine. The presence of mineral matter in large quantity may give a water an unpleasant taste and also make it impossible for use in boilers. On the other hand, water containing a large excess of certain mineral components may have some medicinal value and may become popular as a "mineral water" as distinguished from a "table water."

The number of commercial springs in the United States from which water was sold in 1923 numbered 474, furnishing about 44,400,000 gallons of water to customers at a cost of about $6,400,000, of which $870,000 was the value of medicinal waters. In addition there were 7,300,000 gallons of spring water used in the manufacture of soft drinks.

The imports of medicinal waters aggregated 723,000 gallons valued at $280,000, most of which came from France.

In value of mineral water sold Indiana leads, followed in order by Maine, California and Virginia. Wisconsin

TABLE VI.—ANALYSES OF CONSTITUENTS DIS

	I	II	III	IV	V	VI	VII
Cl	53.08	60.83	42.00	.57	.03	18.19	2.42
Br	.51	.07	1.13	.....	.....	Tr.	....
I	.02	Tr.	.02	.....	.....	Tr.	....
SO_4	6.03	.02	.08	69.87	70.93	46.66	.54
CO_3	2.34	1.23	18.59	4.75	.....	4.11	55.92
PO_4	.....	.....	Tr.	.....	.23	Tr.	....
B_4O_7	.....	.....	Tr.	.....	.....	Tr.	....
Na	31.47	23.45	27.62	2.99	1.25	11.72	1.92
K	.96	.35	.78	.35	.23	.78	.73
Li	.....	Tr.	.08	.....	.....	Tr.	....
NH_4	.....	.03	.....	.22	.....	.....	....
Ca	3.56	7.28	6.03	7.63	7.08	13.16	29.28
Mg	1.57	3.12	3.41	13.18	.93	5.21	3.15
Mn	.....	.10	.....	.....	.78	.....	.91
Fe″	.....	2.39	.....	.....	.03	.....	2.28
Fe‴	.....	.....	.....	.....	11.09	.....	
Fe_2O_3	.....	.....	.03	.02	3.09	.....	.43
Al_2O_3	.....	.....	Tr.				
Al	.....	.....	.....	.....	.....	Tr.	....
SiO_2	.16	.30	.14	.42	1.61	.17	2.42
H_2SO_4	.....	.....	.....	.....	.....	.....	....
HNO_3	.....	.....	.....	.....	.....	.....	....
HCl	.....	.....	.....	.....	.....	.....	....
H_3BO_4	.....	.....	.....	.....	.....	.....	....
TOTAL	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Parts per million of water	11,068.00	6,617.00	12,022.00	62,371.00	8,150.00	4,417.00	499.00

I. Upper Blue Lick Spring, Ky. (Chloride.) Also 0.30 of Al_2O_3, Fe_2O_3 and $Ca_3(PO_4)_2$.

II. Chloride of Iron Spa, Harrogate, Eng. (Chloride.) Contains also 0.07 Sr, 0.76 Ba, and traces of Cu.

III. Congress Spring, Saratoga, N. Y. (Chloride.) Contains also 0.09 Ba and traces of F and Sr.

IV. Bitter Spring, Laa, Austria. (Sulphate.)

V. Roncegno, Tyrol. (Sulphate.) Contains also 1.93 H_3AsO_4, 0.17 Co, 0.41 Ni, 0.06 Zn, and 0.15 Cu.

VI. West Baden Spring, Ind. (Sulphato-chloride.) Contains also traces of Fe, Ba and Sr, and 32.5 parts H_2S per million of water.

VII. Excelsior Springs, Mo. (Carbonate.)

VIII. Virginia Hot Springs, Va. (Mixed type.)

IX. Chalybeate Spring, Mittagong, N. S. W. (Chalybeate.)

SOLVED IN THE WATER OF VARIOUS SPRINGS

VIII	IX	X	XI	XII	XIII	XIV	XV	XVI
.64	27.34	1.27	Tr.	16.49	.....	.32	.....	11.69
....	....	Tr.	.....	.....	.....	.....	.....	.....
....	....	Tr.	.....	.03	.....	.....	.....	.....
21.73	....	3.93	29.22	Tr.	22.11	68.21	67.66	10.64
40.02	30.58	41.47	.....	21.96	.....	.....	.....	.....
....	....	.03	.....	.....	Tr.	Tr.	.....	1.91
....	....	....	.....	25.61	.....	.....	.....	Tr.
1.81	7.13	2.38	12.15	24.99	.26	.22	.73	.75
2.04	8.96	.80	2.05	Tr.	.44	.11	.24	.59
....	....	Tr.	Tr.	.....	.....	.01	.01	.....
....	....	.03	.....	7.88	.....	.....	22.85	.....
23.35	4.25	23.54	Tr.	Tr.	3.70	.38	1.18	2.30
5.82	5.89	2.56	Tr.	Tr.	.50	1.11	.36	.34
....	....	.17	.....	.....	.....	.69	.....	Tr.
....	15.85		.....	.....	2.17	1.19	Tr.	.....
....			.....	.....	.....	.....	.....	5.98
....	....	.10	5.80	.....	.....	.....	.....	.....
.58	....			.40	.....	.....	.....	.....
....	....	....	.....	.....	1.20	11.08	.10	.35
4.01	....	22.85	50.78	2.64	.....	7.11	2.67	.03
....	....	....	.....	.....	69.62	9.37	1.29	.....
....	....	....	.....	.....	.....	Tr.	.....	.....
....	....	....	.....	.....	.....	.....	.18	65.42
...	....	....	.....	.....	.....	.....	2.73	.....
100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
563.00	225.00	199.00	473.00	5,343.00	6,161.00	464.00	3,365.00	158,051.00

X. Big Iron Spring, Hot Springs, Ark. (Siliceous.) Contains also 0.23 NO_3, 0.64 BO_2 and traces of Ba and Sr.

XI. Bench Spring, Upper Geyser Basin, Yellowstone National Park. (Siliceous.)

XII. Hot Spring, Sulphur Bank, Clear Lake, Cal. (Borate.)

XIII. Tuscarora Sour Spring, Brantford, Can. (Acid.)

XIV. Rockbridge Alum Spring, Va. Contains also 0.07 Ni, 0.05 Co, 0.08 Zn and a trace of Cu.

XV. Devil's Inkpot, Yellowstone National Park. (Acid.)

XVI. Hot Lake, White Island, N. Z.

Nos. XIII and XIV are acid springs issuing from sedimentary rocks, whereas Nos. XV and XVI are associated with recent vulcanism.

leads in the value of table water sold and is followed by New York, California and Maine. One of the reasons for the popularity of the Wisconsin springs is the fact that they yield a comparatively soft water in a region in which the well water is hard.

Clarke[12] classifies mineral spring water as: chloride, sulphate, sulphato-chloride, carbonate, sulphato-carbonate, chloro-carbonate, chloride-sulphate-carbonate, siliceous, borate, nitrate, phosphate and acid waters.

A few analyses of some popular table waters and a few types of mineral waters are given above. They are quoted from Clarke's "Data of Geochemistry," unless otherwise noted.

If the water of a well or spring contains nitrates, nitrites or chlorine in abnormal quantities, their presence suggests pollution from surface sources, as these substances are commonly derived from organic matter. Very small quantities of nitrates and nitrites are suggestive of pollution. The quantity of chlorine that may occur in water without causing suspicion varies with the location of the well or spring, as in some places it may be dissolved from the rocks, in others it may come directly or indirectly from the sea or from salt lakes, and in still others, it may result from intermixture with connate water buried with the rocks serving as the reservoir supplying the well, or percolating into them from adjacent sediments.

That which comes from the sea or salt lakes may be introduced into the ground water in two ways. The salt water may force its way down bedding planes, joints, or fault fissures that outcrop under the sea and dip toward the land, or it may come from salt spray carried inland with dust particles and precipitated with the rain (Fig. 5). The chlorine decreases as waters farther and farther inland

[12] Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 181–203, 1924.

are tested, furnishing an opportunity for preparing maps giving lines of equal chlorine content (normal chlorine lines or isochlors), which represent the percentages of chlorine that may be expected in the waters of the various belts. In either case the shallow wells and springs nearer the shore will normally produce water with more chlorine

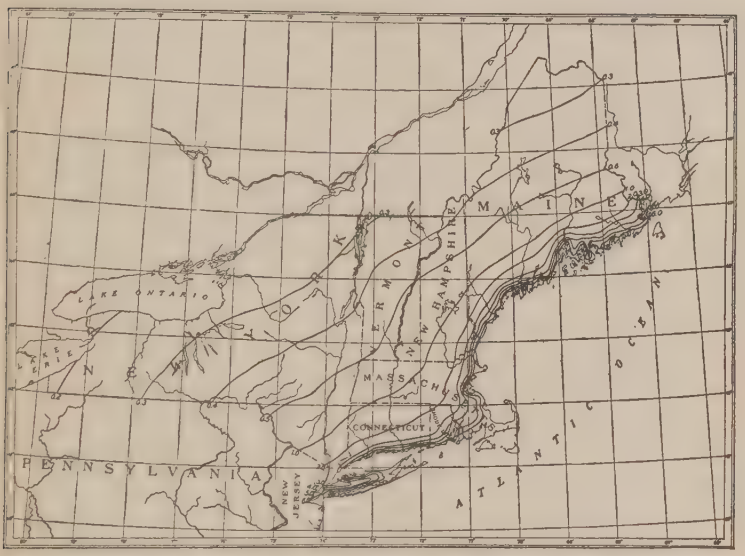


FIG. 5.—Isochlors crossing New England and New York. The figures show parts of chlorine per million of water. (*After Jackson, U. S. Geol. Sur., Water-Supply Paper, 144.*)

than those farther from the shore.[13] If a water contains no more than the expected amount of the element it may be regarded as safe unless it contains nitrates and nitrites, but if it contains an excess over the expected amount it is to be avoided irrespective of the amount of nitrogen compounds it contains, since all salt found in water that is not derived from mineral deposits, connate supplies, or the sea must come from domestic drainage.

[13] Cf. Jackson, D.D., U. S. Geol. Sur., *Water-Supply Paper*, 144, 1905. Pls. II, III, IV and V.

For surface waters the normal chlorine lines near bodies of salt water hold with great accuracy, but since the underground water is in constant circulation they are not of great value in estimating the character of underground waters and should not be depended upon. In the water of protected wells the chlorine is usually somewhat above the normal for the surface waters in the same neighborhood, due to the chlorides dissolved from the rocks. In open wells excess chlorine is usually due to the entrance of polluted surface waters.

In portions of the country at a considerable distance from bodies of salt water the isochlors show no such regular arrangement as they do in regions near bodies of salt water. On the contrary they are irregular lines the positions of which are determined by local conditions, such as the presence of buried salt beds or of drainage from bodies of connate brines. Unless located with extreme care they have little significance and are of slight use in determining the purity of a water.

Classification.—With respect to their openings springs may be classified[14] as:

Seepage or filtration springs
Fracture springs
  a. Fissure springs
  b. Joint springs
Tubular springs

Seepage springs are those in which the water gradually seeps from loose material, usually along the top of an impervious layer, or from the sides of valleys cut into the zone of saturation of more or less uniform water-bearing deposits (Fig. 6).

The water of a fracture spring issues from a more or less

[14] Fuller, M. L., "Underground Waters for Farm Use," U. S. Geol. Sur., *Water-Supply Paper*, 255, 1910.

well-defined fissure along bedding, joint, cleavage, or fault planes (Fig. 7).

The water of tubular springs flows through more or less tubular passages in the glacial drift or solution cavities in limestone. Many of the passages in limestone are so large

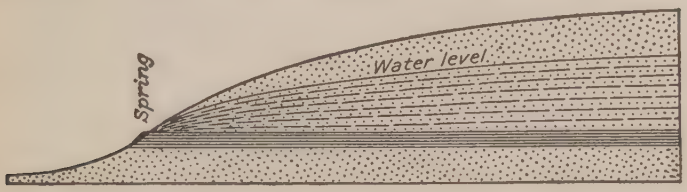


FIG. 6.—Seepage spring at upper surface of an impervious layer. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

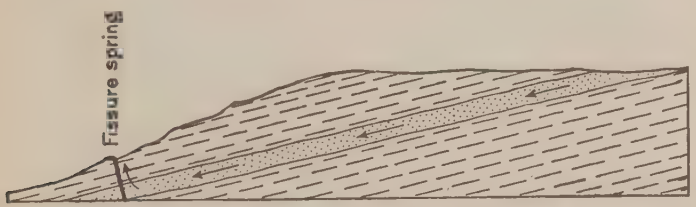


FIG. 7.—Fissure spring, issuing from crack penetrating a water-bearing layer. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

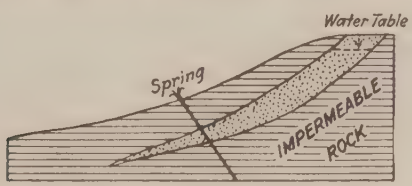


FIG. 8.—Another type of fissure spring. (*After Meinzer, U. S. Geol. Sur., Water-Supply Paper, 494.*)

as to accommodate sizable streams (Figs. 8, 9 and 10). For instance, the Silver Springs of Florida furnish enough water to form a river which is navigable all the way from the ocean to the mouth of the spring (Fig. 11).

Another method of classification of springs refers to the

causes that produce the flowage.[15] Thus springs may be divided into (A) gravity springs, where the water issues from an outcrop of the water table, including (*a*) depression and (*b*) contact springs; (B) artesian springs, where the water issues under hydraulic head through a fissure

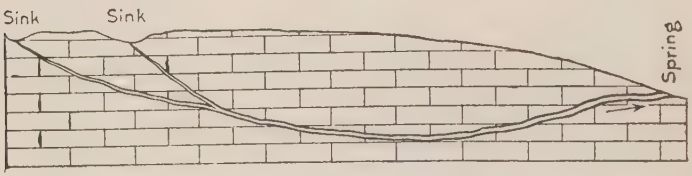


FIG. 9.—Tubular spring at exit of water course in limestone. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

FIG. 10.—Mouth of water course in gypsum. (*Photo by V. H. Barnett, U. S. Geol. Sur., Water-Supply Paper, 489.*)

extending down into an aquifer (water-containing bed) confined between impervious beds; (C) volcanic springs, where associated with vulcanism, and, (D) springs associated with deep fractures that apparently extend far

[15] Meinzer, O. E., "Outline of Ground-water Hydrology," U. S. Geol. Sur., *Water-Supply Paper*, 494, 1923.

beneath the water table. The last two classes usually yield warm or hot water.

Discharge.—The discharge of springs varies widely for different springs and often for the same spring at different times. If the discharge is continuous, whether variable or not, the spring is said to be perennial: if discharge occurs only during certain periods the spring is said to be intermittent. A geyser is an intermittent spring in which the discharge is caused at fairly regular and comparatively

FIG. 11.—General view of Silver spring, Marion County, Fla. (*Photo by Roswell Allen Studios, Ocala, Fla.: U. S. Geol. Sur., Water-Supply Paper, 557.*)

short intervals by the expansive force of superheated steam. Geysers are confined to volcanic districts. Periodic springs are also intermittent springs. Their periods of discharge and rest are rhythmic like those of geysers, but the cause of their periodicity is not steam and they are not limited to volcanic regions. Most periodic springs are in limestone and their rhythmic action is supposed to be due to the fact that their channels of discharge are siphons.

Permanent, or perennial, springs naturally have the greatest discharge. That of Silver Spring ranges between 342 and 822 second-feet.[16] The discharge of Malade

[16] One second-foot of water is equal to about 646,000 gallons daily.

Springs in the Snake River in Idaho is 1,060 second-feet and that of the Giant Springs, near Great Falls, Montana, about 600 second-feet.

The water of most of the Snake River Springs issues from a bed of scoriaceous or shattered basalt overlying denser rocks, and that of the Giant Springs flows from joint cracks in a coarse-grained sandstone.[17]

The discharge of Silver Springs is exceptional, but many tubular springs are large, since they are merely the places of issue of underground streams. Springs of the more usual kind—those that tap the ground water layer—may also discharge large quantities of water, but large springs of this type are not as numerous as large tubular springs. Some of the most noted are the Champion Springs at Saratoga, New York, which flow at the rate of 2,500 gallons hourly, Glen Springs, Waukesha, Wis., that yield 45,000 gallons hourly, and the Warm Sulphur Springs, Bath, Va., that yield 360,000 gallons in the same period.

Temperature of water.—With respect to the temperature of the water which they discharge, springs may be cold, if their water is appreciably below the mean annual temperature of the localities in which they exist, or thermal, if they yield water appreciably warmer than the surrounding air, i.e., greater than about 70°. A warm spring is a thermal spring yielding water with a lower temperature than that of the human body, i.e., between 70° F. and 98° F., and a hot spring is one that yields water warmer than 98° F.

The temperature of the water issuing from the Sweet Springs, W. Va., is 74° F., that of Warm Springs, Tenn., is 95° F., that of Hot Springs at Bernardino, Cal., is 108°–

[17] For a description of the large springs in the United States, i.e., those yielding 100 second-feet of water or more, see Meinzer, O. E., "Large Springs in the United States," U. S. Geol. Sur., *Water-Supply Paper*, 557, 1927.

172° F., and that of the Hot Springs at Washita, Ark., is 140°–156° F.

In some places the heating is due to the addition to the ground water of hot water from magmatic sources, in others to the presence of igneous rocks of high temperature near the openings through which the water travels, in others to the passage of the ground waters through masses of rock that have been heated by friction attending faulting, folding or other types of deformations, or in which rapid chemical action is taking place. Finally meteoric water may have been carried to great depths during its passage from the surface to its point of exit.[18]

ARTESIAN WELLS

Since the earth's crust is made up largely of series of sedimentary beds that may be gently folded, contorted

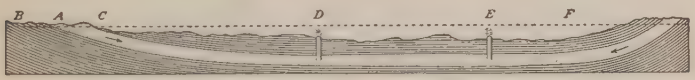


FIG. 12.—Figure illustrating conditions existing in an artesian basin, A, Porous stratum; B, C, impervious beds, acting as confining strata. (*After Fuller, U. S. Geol. Sur., Bull. 319.*)

or closely compressed and may be intricately involved with igneous or metamorphic rocks, it is evident that the ground water cannot exist as a uniform layer within the crust, as it might if the crust were uniform in character. When porous sedimentary beds are separated from one another by impervious layers through which water cannot penetrate, the porous beds may contain stores of water that exist under conditions different from those affecting ground water in general (Fig. 12). This water being in a conduit, when free to escape, obeys in general the laws

[18] For a discussion of the causes of high temperatures of some spring-waters see the series of articles by Kirk Bryan in the *Jour. of Geol.*, Vol. xxxii, Nos. 3, 4, 5 & 6, 1924.

governing the flow of water in pipes. Its abundance is dependent largely upon the porosity, and its character upon the composition of the conduit. Perhaps, as a rule, the composition of the conduit material—the aquifer—is different from that of the material surrounding it, and as a result its water is of a different character from that of the mass of ground water in the vicinity. If the aquifer is a

FIG. 13.—Artesian Well, about 5 miles east of Sturgis, S. D., at base of Beaver Bluff. The delivery pipe is 8 in. in diameter. When open a column of water is thrown to a height of 35 ft. (*Photo by A. G. Eldredge.*)

sandstone in a series of limestone beds, its water may be "soft," while that of the general ground water may be "hard." Moreover, since the aquifer is sealed it may furnish water in an arid region where the water table is too low to be within reach of ordinary wells.

Water enclosed in such conduits and in underground streams (pp. 45, 48) is commonly known as artesian water, and the opening which taps it as an artesian well. It may be delivered under pressure sufficient to raise it above the surface causing a flowing well (Fig. 13), or under a head sufficient to raise it only partly to the surface.

Conditions controlling supply.—The conditions which control the delivery of artesian water are best described by Fuller.[19]

Among these conditions the most important are the following:

1. The water capacity of the aquifer.

This depends upon its porosity, the size and abundance of joint cracks, the presence or absence of definite bedding planes, the presence or absence of breccia cavities, or of solution or gas cavities.

2. The texture of the material of the aquifer.

This determines the rate of flow, which in turn determines the rapidity of delivery and naturally affects the pressure under which the delivery is made.

The rate of movement varies with the coarseness of grain of the water-bearing layer, and the difference in elevation between the source of its supply and the point of delivery.

In some rocks the movement is very slow and in others as great as 12 feet per day. It has been estimated that the artesian water tapped in the southern part of the State of Wisconsin has taken two or three hundred years to flow from the northern part of the State where the aquifer outcrops. Because the rate of flow in the aquifer is determined by its storage capacity and texture, it is evident that the supply of water that can be delivered to a well in a given time is limited. Excessive pumping may exhaust the supply faster than it can be received and, as a result, the quantity of water that may be obtained will be greatly reduced. If within a circumscribed area a number of wells are being pumped faster than water can be furnished them it may be necessary to cease pumping at intervals in order to allow a sufficient supply to accumulate

[19] Fuller, M. L., "Summary of the Controlling Factors of Artesian Flows," U. S. Geol. Sur., *Bull.* 319, 1908.

before pumping can again become profitable. The danger of over pumping is well illustrated by the case of a certain group of wells in Chicago,[20] some of which originally delivered their water 80 feet above the surface or 111 feet above Lake Michigan, but which at present are unable to lift it above a height of 150 feet below the surface. The graph (Fig. 14) shows the lowering of the static head at

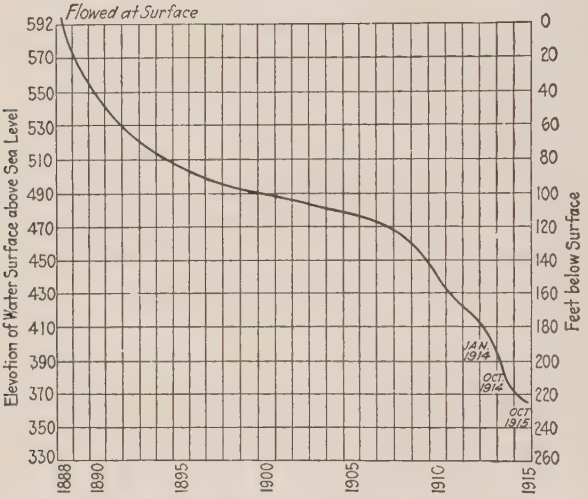


Fig. 14.—Graph showing lowering of static head in Chicago Stock Yards wells, since they flowed in 1889. (*After C. B. Anderson, Ill. Geol. Survey.*)

the stock yards between 1889 and 1915. In 1914 the five wells in this district pumped 7,315,200 gallons daily.

3. An adequate source of supply.

Naturally, unless water enters a porous bed none can be delivered by it. The most favorable condition yielding an adequate supply is furnished by a broad outcrop of the aquifer on a mountain side.

[20] Cf. Anderson, C. B. and DeWolf, F. W., "Artesian Waters in Chicago and the Surrounding Territory," Ill. Soc. Eng., *Ann. Rep.*, Vol. 30, pp. 69–72, 1915, and Anderson, C. B., Ill. State Geol. Sur., *Bull.* 34, pp. 88–102, 1919.

If the outcrop is broad the collecting ground is large. If the outcrop is on a mountain side the rainfall is usually abundant and the head at the well is noticeable.

4. The presence of a satisfactory seal above and below the water-bearer, for if the seal is not perfect the water will escape and the head will be lost.

The most satisfactory seals are layers of shaly rocks, or clays, compact igneous or other rocks, or coatings of platy minerals made between rock layers by shearing along their bedding planes.

5. The absence of opportunity for drainage, other than the well opening.

If the aquifer is cut into by a valley or gorge, discharge may be made through the outcrop on its sides.

These are the conditions requisite for the delivery of water under pressure from bedded rocks serving as conduits.

Fuller, however, calls attention to the fact that artesian water is not found only in bedded porous rocks between impervious layers. In some instances the effects of the conditions just cited may be produced by other factors. Thus, solution channels in a limestone may become clogged and the water flowing through them may be impounded, and if tapped by a well may yield water under pressure (Fig. 15.)

The only three essentials demanded for artesian flow according to Fuller, are:

1. Adequate water supply, from any source whatsoever
2. A retaining agent offering more resistance to the passage of water than a well-opening, and
3. An adequate source of pressure

The retaining agent may be a stratum of impervious, or nearly impervious, rock, a vein or a dike, a filled joint or fault crack or a layer of water enclosed in the capillary

openings of an overlying fine-grained rock. The pressure is due primarily to variations in level of the artesian system.

The geological factors that influence the second and third requisites are:

1. Character of the reservoir
2. Nature of the retaining agents
3. Structure of the reservoir
4. Topographic and other conditions above the aquifer that affect supply in the catchment areas
5. Conditions affecting leakage

Any rock furnishing opportunities for the storage of water under pressure may become a source of artesian supply. A basin of bedded rocks, varying in porosity and outcropping at comparatively high levels at its bor-

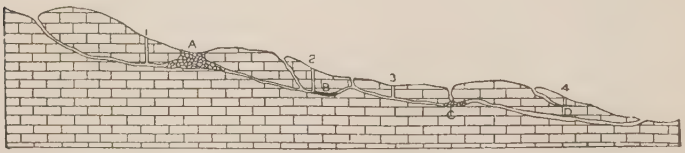


FIG. 15.—Section illustrating conditions of flow from solution passages in limestone. A, Brecciated zone (due to caving of roof), serving as confining agent to water reached by well 1; B, silt deposit filling passage; C, surface debris clogging channel; D, pinching of crevice, confining water reached by well 4. (*After Fuller, U. S. Geol. Sur., Bull. 319.*)

ders, is the type of system generally thought of as fulfilling most satisfactorily the conditions for furnishing artesian water (Fig. 12), although artesian flows from uniform horizontal beds are common, especially in drift deposits. Flows down the bedding planes of non-porous rocks are not infrequent. Those from clogged solution passages are common (Fig. 15). Flows occur also from lamination planes, fault cracks and joints.

Joints furnish one of the most widespread types of artesian systems, as nearly all crystalline rocks and all jointed sedimentary rocks contain water. Their supply is not large but it can nearly always be depended upon to furnish some water under pressure.

FIG. 16.—Section illustrating artesian conditions in joints within crystalline rocks. A, C, E, conditions under which flowing wells may be obtained; B, D, S, conditions under which no water may be found; A, conditions under which well may be polluted by surface drainage entering cracks near mouth of well. (*After Fuller, U. S. Geol. Sur., Bull. 319.*)

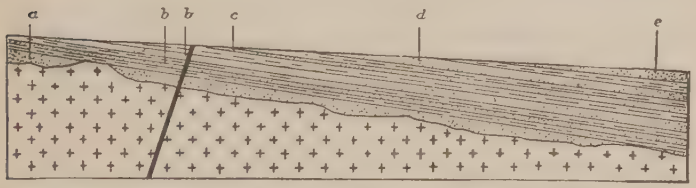


FIG. 17.—Section of an artesian slope. *a*, Water bed cut off by unconformity; *b*, beds cut off by dike; *c*, bed in which friction is the only obstruction to downward motion; *d*, porous bed changing to impervious; *e*, bed pinching out farther to the right.

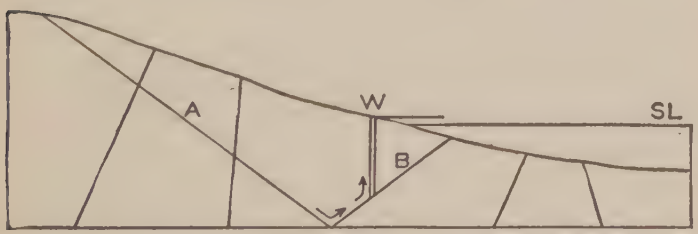


FIG. 18.—Section illustrating action of salt water as a confining agent, etc., SL, Sea level; A, open joint bringing down fresh water; B, open joint communicating pressure from heavier salt water; W, well slightly above sea level, obtaining flow in consequence of small rise in head resulting from slightly greater pressure of water in joint B as compared to the water column in the well, due to the higher specific gravity of the salt water.

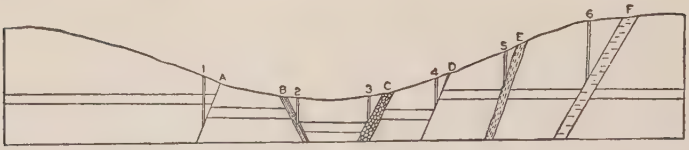


FIG. 19.—Ideal section illustrating possible conditions of flow from fault and contact planes. A, Reverse fault affording pump water to well 1, but no flow; B, sheet zone due to normal faulting feeding flowing well 2; C, crushed zone due to normal faulting yielding water to well 3; D, simple normal fault feeding well 4; E, vein affording water from contact to well 5; F, dike affording water from contact to well 6. C, E, or F, may also be conceived to represent sandstone dikes which may under certain conditions become important artesian reservoirs.

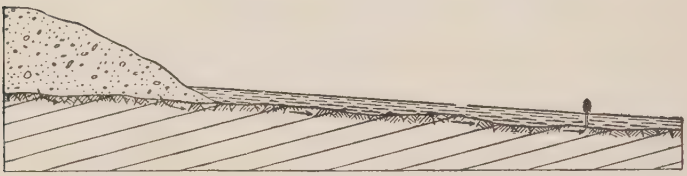


FIG. 20.—Section illustrating conditions of flow from joints and cracks in stratified rocks covered by impervious layers and fed from drift. (*After Fuller, U. S. Geol. Sur., Bull. 319.*)

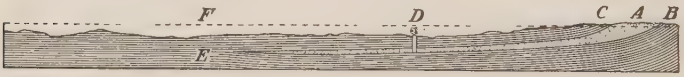


FIG. 21.—Diagram showing impounding of water in a tapering sand layer enclosed by impervious beds. (*After Fuller, U. S. Geol. Sur., Water-Supply Paper, 255.*)

Fuller[21] illustrates various types of artesian systems by the diagrams reproduced on pages 55 and 56.

Character of water.—Since artesian water is particularly valuable as a substitute for unsatisfactory surface water in many industries the matter of its quality is of great concern.

The greater part of the water in nearly all artesian systems is meteoric. As the rain water finds its way below

[21] Fuller, M. L., "Summary of the Controlling Factors of Artesian Flows," U. S. Geol. Sur., *Bull.* 319, pp. 38–42, 1908.

TABLE VII.—ANALYSES OF THE WATERS OF SOME ARTESIAN WELLS

	Percentages in Dissolved Salts				*Parts per Million of Water*			
	I	II	III	IV	V	VI	VII	VIII
Cl	61.65	55.83	.48	18.02	66.9	1790.0	...	58.0
Br	.29	.04	....	....	....	....	...	...
I	Tr.	.03	....	....	....	....	...	...
SO_4	.07	3.12	66.28	33.22	71.1	122.0	13.0	63.0
CO_3	....	2.63	.60	13.14	791.5	....	36.0	140.0
Na	31.57	33.09	30.46	26.88	668.7	465.0	7.9	46.0
K	Tr.	.27	1.08	.79	6.4	140.0	0.5	...
Ca	4.85	3.72	.67	5.26	4.4	404.0	19.0	214.0
Mg	1.52	1.13	.41	2.23	2.5	131.0	2.2	32.0
Mn	Tr.	....	Tr.	....	Tr.	....	...	...
Fe″	.05	....	....	....	2.4	}	0.51	}
Fe_2O_3	....	.06	....	.07	....	} 1.4	...	} 1.0
Al_2O_3	....	....	....	.04	3.4	}		}
SiO_2	Tr.	.08	.02	.35	51.0	194.7	18.17	17.0
	100.00	100.00	100.00	100.00	....	....	...	...
Solids per Million	178,900.00	10,589.00	74,733.00	3,008.00	1,668.3	4,056.0	98.00	834.0

I. Artesian Well, Abilene, Kansas. Natural brine.

II. Artesian Well, Cincinnati, Ohio. Contains also free H_2S and CO_2.

III. Well, 130 feet deep, 14 miles northwest of Abilene, Kansas. Contains traces of NO_3 and Fe.

IV. Deep Well, Macomb, Illinois.

V. Artesian Well, La Junta, Colorado. Well, 386 feet deep. Contains also a trace of Li.

VI. Glue factory, Vinalhaven, Maine. Well, 230 feet deep in granite. Contains also 1,046 parts organic and volatile matter.

VII. South Poland. Well, drilled in granite. "Apollo water." Contains also trace of Li.

VIII. Bangor House. Well, drilled in slate, 290 feet deep. Contains also 150 parts organic and volatile matter.

N.B.—Analyses VI, VII, and VIII are quoted from *Underground Waters of Southern Maine*, by Frederick G. Clapp, with records of deep wells by W. S. Bayley: U. S. Geol. Sur.,

Water-Supply Paper, 223, pp. 77–79, 1908. The differences between the summation of the constituents and the total solids per million may be due to the fact that the total solids are the residue left on evaporation and include therefore "water of crystallization," and some undetermined constituents.

the surface it dissolves small quantities of organic and mineral matter. This increases in amount with increasing depth and is naturally greater in limestone regions than in those underlain by siliceous rocks. If the artesian system consists of joints, faults, bedding planes, etc., the character of the water will reflect the character of the rocks from which it is obtained. Water from limestone will be hard, whereas that from siliceous rocks will be soft. However, in an artesian basin of bedded rocks it is not unusual to find a layer of sandstone between limestone beds. If the sandstone is an aquifer it may furnish soft water to a well that penetrates it, whereas, other wells in the vicinity, which do not enter the sandstone, may furnish hard water.

The composition of the waters of certain artesian wells is shown by the analyses on page 57, which unless otherwise indicated are from Clarke's "Data of Geochemistry."

In many districts a knowledge of the possible sources of artesian water is so important to manufacturing and other industries and to municipalities that maps are made which show the depths at which satisfactory sources of artesian supply may be reached. Such maps are of special value in arid and semi-arid regions and in those in which surface and ordinary well water are objectionable. Many maps of this kind[22] have been published by the U. S. Geological Survey.

[22] See U. S. Geol. Sur., *Geol. Atlas*, Pueblo folio (No. 36), Walsenburg folio (No. 68), St. Mary's folio (No. 136) and Patuxent folio (No. 152).

CHAPTER IV

PETROLEUM AND NATURAL GAS

COMPOSITION AND PROPERTIES OF PETROLEUM

Composition.—Petroleum is a naturally occurring liquid composed of hydrocarbons mixed with small quantities of sulphur compounds and oxidized nitrogenous substances.

Although members of nearly all the series of hydrocarbon compounds are in petroleums from one or another locality, two series are much more common than the others. These are the marsh gas, or methane, series (C_nH_{2n+2}) and the olefine and naphthene series (C_nH_{2n}). The lower members of the series are gases, the intermediate members liquids and the higher members solids at room temperatures. Their specific gravity increases with the greater number of atoms present in the molecule and consequently the gravity of the oil increases with increase in the proportion of the higher members present in it. Of the marsh gas series the predominant liquid members are:

TABLE VIII.—BOILING POINTS AND SPECIFIC GRAVITIES OF SOME COMMON COMPONENTS OF PETROLEUM

Compound	*Formula*	*Boiling Point*	*Gravity at 60° F. in Beaumé Degrees*
Pentane	C_5H_{12}	36.3 C.	92
Hexane	C_6H_{14}	69.0	85
Heptane	C_7H_{16}	98.4	76
Octane	C_8H_{18}	125.5	71
Nonane	C_9H_{20}	150.0	66
Decane	$C_{10}H_{22}$	173.0	63

In addition to these are the dissolved gases CH_4, methane, C_2H_6, ethane, C_3H_8, propane and C_4H_{10}, butane.

In this series the higher members are the paraffins, therefore scales of these substances are produced when the heavier distillates are cooled. Oils composed mainly of this series of hydrocarbons are said to have a *paraffin* base.

Oils composed mainly of the olefine and naphthene (C_nH_{2n}) series of hydrocarbons, with smaller quantities of the acetylene (C_nH_{2n-2}) and benzene (C_nH_{2n-6}) series yield on evaporation a black tarry asphaltic residue composed largely of hydrocarbons of the naphthene series. They are said to have an *asphalt*, or a *naphthene*, base. Many oils are now known to contain both paraffin and asphalt bases so this distinction is no longer of significance. California and parts of Texas produce asphalt base oils; Pennsylvania and West Virginia paraffin oils and Illinois those with mixed base.

Until recently the paraffin oils were regarded as more valuable than the asphalt base oils because more readily refined; but methods are now known by which the latter are made to yield as valuable products as the paraffin oils, though paraffin base oils still command the higher price.

In addition to the hydrocarbons some oils contain sulphur as H_2S, others as free sulphur, or as sulphur in organic compounds. When in the latter form it is difficult to remove, and if left gives a bad odor to the distillates.[1] Other oils contain nitrogenous compounds, and others traces of phosphorus.

Moreover, all petroleum contains small quantities of the organic compounds *cholesterin* or *phytosterin*, which are circularly polarizing, consequently all oil, or nearly all, is circularly polarizing. As these substances are known only in the fats of animals and vegetables and their derivatives, it is concluded that petroleum must be of or-

[1] Gasoline must contain less than 0.1% sulphur to conform to government specifications for motor fuel.

ganic origin and since cholesterin, which is of animal origin, is much more common than is phytosterin it is believed that optically active oils are as a rule of animal origin.

Color.—Most oils are opaque or nearly so by transmitted light and have a dark green cast by reflected light. As a rule the paraffin oils are yellow, brown or red and the asphaltic oils dark brown, dark red, green or black.

Odor.—The odor of oil containing no sulphur is usually pleasant and the oils of this kind are known as "sweet oils," while those containing sulphur have disagreeable odors owing to the presence of hydrogen sulphide, carbon bisulphide or of some other sulphur compound, hence these are known as "sour oils." Sour oils usually occur in limestones.

Boiling, flashing and freezing points.—Crude oil freezes between ranges of 0° F., in some Italian oils, and 82° F., in some Burma oils. Their flashing points (temperatures at which they ignite) vary between 0° F., in Italian oils, and 370° F., in an oil produced on the African Gold Coast. Boiling points vary between 180° F., in some Pennsylvania oils and 338° F., in oils from Hanover, Germany. Of these, the boiling points are the most significant. Freezing points affect the ease of transportation in pipe lines, it is true, but the boiling points indicate the character of the mixture and enable one to estimate the value of the oil for refining purposes. The low boiling oils contain the lighter components in larger quantities and consequently in the refining process yield larger proportions of the lighter distillates. They are more easily refined to valuable products and there is little loss by the production of the heavier, cheap products. Moreover, the paraffin oils are more valuable than asphaltic oils of the same specific gravity, because of the greater quantity and higher quality of the naphthas and illuminating oils they yield and the greater value of the residue.

Specific gravity.—The specific gravity of crude petroleum is usually between 0.782 and 0.850, but may be greater or less than this in exceptional cases. It is measured in terms of the Beaumé scale on which 10° represents a specific gravity of 1.0 at 60° F. and 95° a specific gravity of 0.6222.[2] The formulas for transforming the scale and specific gravity are $\frac{140}{\text{Bé}^\circ + 130} = \text{specific gravity}$, and $\frac{140}{\text{Sp. gr.}} - 130 = \text{Bé}^\circ$. Thus the lower the Beaumé scale the higher the specific gravity.[3]

Table IX.—Specific Gravities and Beaumé Scale Records of Well-known Crude Oils

Source of Oil	*Sp. gr.*	*Beaumé Scale*
Placerita Canyon, Calif.	.777	50.0
Pennsylvania	.801– .817	46.2–42.6
Ohio	.816– .860	42.8–32.5
Kansas	.835	38.8
Spindletop, Texas	.904– .925	24.8–21.1
Wyoming	.912– .945	23.3–11.9
California (heavy oils)	.920–1.007	21.9– 9.9

[2] Panyity, L. S., *Prospecting for Oil and Gas*, Table, pp. 238–239, 240. New York, 1920.

[3] The Beaumé scale as given above is the one originally invented. There is another, however, which has gradually come into use. In order to overcome the confusion incident to the employment of two different scales to designate the same property the American Petroleum Institute, the U. S. Bureau of Mines and the U. S. Bureau of Standards have agreed to recommend that, in the future, only a scale based on the modulus 141.5 (instead of 140) be used in the petroleum industry, and that it be known as the A. P. I. scale. The relation of degrees A. P. I. to specific gravity is expressed by the formula

$$\text{Degrees A. P. I.} = \frac{141.5}{\text{Sp. gr.}} - 131.5$$

The same specific gravity registers a little higher on the A. P. I. scale than on the Beaumé scale. (See National Standard Petroleum Tables: Circular of the Bureau of Standards, No. 154. Washington, 1924.)

Naturally the weight of a barrel of oil depends upon the specific gravity of the oil it contains. A barrel of crude oil of Bé. 10° weighs 350 lbs., of 20°, 327 lbs., of 30°, 307 lbs., of 40°, 288 lbs., of 50°, 276 lbs., of 60°, 258 lbs., of 70°, 245 lbs., and of 80°, 238 lbs.

The proportions of distillates produced at different temperatures from oils of different specific gravities are shown below.[4]

TABLE X.—RELATION BETWEEN FRACTIONS DISTILLED AT SPECIFIED TEMPERATURES AND SPECIFIC GRAVITIES OF CERTAIN OILS

Source of Oil	*Gravity, Bé°*	*Fractions (in volumes)*				
		Distillates		*Residuum*	*Paraffin per cent*	*Asphalt per cent*
		Below 150° C.	150° *to* 300°C.			
St. Mary's, W. Va..	47.9	16.50	41.00	34.50	5.00	0.00
Morris, Okla.....	35.5	3.00	34.00	62.10	11.90	0.00
Humboldt, Kansas.	27.7	1.00	29.00	68.90	3.93	2.33
Beaumont, Texas..	22.1	6.45	35.00	58.55	....	6.34
Beaumont, Texas..	21.9	1.80	17.10	81.10	....	7.50
Kern River, Calif...	15.7	....	20.20	79.80	....	21.40
Sunset, Calif.....	9.9	....	5.00	95.00	....	51.00

The distinction between the heavier and the lighter oils, however, is gradually becoming less and less important, since the discovery of the cracking process by which the heavier components of the crude oil and the heavier distillates are broken down by destructive distillation in pressure stills into lighter, more simple compounds which are then distilled like the lighter oils.

Products.—The average yield of products by methods of distillation designed to produce the lighter fractions is approximately as follows:

[4] Extracted from table assembled by Ries, *Econ. Geology*, fifth Edition. New York, pp. 74–78, 1925.

TABLE XI.—AVERAGE YIELD OF PRODUCTS BY DRY DISTILLATION OF PARAFFIN BASE OILS

	Paraffin base oil	*Oil with paraffin and asphalt base*
Light Naphthas	12–15%	6–8%
Heavy Naphthas	12–15%	13–15%
Burning Oils	65–75%	16–18%
Gas and Fuel Oils	.....	20%
Tar and Paraffin Stock	10–12%	42%
Loss	5–6%	.....

In the latter case the tar from the mixed base oil is separated and further distilled yielding:

Paraffin distillate	22%	Cracked distillate	15%
Wax tailings	1%	Coke	4%

The paraffin fraction is the source of paraffin oil and paraffin wax. It has a gravity of 30° Bé., and a freezing point of about 70°. It is treated with sulphuric acid, cooled and pressed through filters separating the wax from the oil, which is redistilled producing fractions that are mixed with the lighter fractions or saved and sold as lubricating oil. The cracked distillate is also redistilled and the fractional distillates are distributed.

In the asphalt oil there are commonly more heavy constituents and fewer lighter ones. Often only the light constituent is distilled off until the remaining oil has a flash-point of 150° F. when distillation is stopped and the residue is stored for use as fuel oil; or if a road oil is to be made the distillation is continued until the residue is a heavy mass that is almost solid when cold.[5]

[5] Ziegler, Victor, *Popular Oil Geology*. Pp. 14–24, New York, 1918; Hager, *Practical Oil Geology*. Pp. 23–35, New York, 1926; Andros, S. O., *The Petroleum Handbook*. Chicago, 1919.

TABLE XII.—AVERAGE YIELDS OF PRODUCTS FROM SOME WELL-KNOWN OILS WITH ASPHALT BASE

	Gasoline Per Cent	*Kerosene Per Cent*	*Gas Oil Per Cent*	*Fuel Oil Per Cent*	*Loss Per Cent*
Electra, Tex.....	25.7	25.9	9.3	36.8	2.30
Mansfield, La.....	10.0	*55.0*	20.0	13.0	2.00
Glenn Pool, Okla....	17.69	17.28	....	*60.64*	4.39
Cushing, Okla.....	*31.0*	25.0	15.0	27.0	2.00

The names applied to the various distillates produced by retorting and refining crude petroleum do not in all cases indicate the same product. Usage differs somewhat in different parts of the country because the different types of oil respond differently to the methods employed in distilling and refining them. Perhaps the specifications in most general use for the different fractions are those given below.

Benzine.....Raw distillate to 52° Bé.
Kerosene.....Raw distillate bet. 52° Bé. and 36° Bé.
Power distillate, gas oil..Raw distillate bet. 36° Bé. and 28° Bé.
Fuel oil.....Not definite
Wax oils.....Distillate of paraffin residuum
Asphalt or paraffin.....Residuum

The refining of benzine gives:

Gasoline.....Finished distillate to 60° Bé.
  Automobile, grade 1st.....60°–61°
  Automobile, grade 2nd.....64°–66°
Naphtha.....Finished distillate to 50° Bé.
  Light naphtha.....54°–56°
  Turpentine substitute.....49°

The refining of kerosene gives:

  High grade kerosene.....44°–46° Bé.
  Intermediate grade kerosene....43°–44°
  Tank wagon kerosene.....40°–42°

The refining of power distillate gives:

Various grades for internal combustion engines
Gas oils

Fuel oil and road oils vary in character depending upon the nature of the crude oil furnished to the refinery. Specifications for road oils are made by the user and the refineries supply the grade specified. They may have specific gravities from 16° Bé. to 34° Bé. Fuel oil, being used for burning to produce heat is valuable in proportion as it contains kindling and combustible components, consequently it may consist of any combination of ingredients that will produce sufficient heat to make it a satisfactory substitute for coal. Tests on locomotives show that 3.62 barrels of good fuel oil are equal in heating power to one ton of bituminous coal producing 13,350 B. T. U.'s.

Lubricating oils are separated from the wax distillates and the residuum. They are usually graded by fire test. Thus automobile and engine oil have a fire test of about 450° F.; cylinder oil of 600° F., and castor oil for use on farm and other light machinery a fire test of 300° F.

The individual characters of the similarly named distillates manufactured by different companies vary so widely, that, in order to secure a uniform product best adapted to the use for which it is intended, it has been found necessary by large users of gasoline, fuel oil, bunker oil and gas oil to draw up specifications for each grade, and to demand that the oils furnished shall conform to these specifications in every detail. The grades of oil supplied to the navy and to the air force of the United States are now standardized, as are also the grades of automobile gasoline offered for sale in many of the States.[6]

[6] "Specifications for Petroleum Products and Methods for Testing," U. S. Bureau of Mines, *Tech. Paper*, 323, 1923.

Uses.—The most important uses of petroleum products are for lighting, heating and lubrication and for producing power. In addition, naphtha is a solvent for resins and benzine is used as a solvent for grease in cleaning, and as a substitute for and an adulterant of turpentine. Astral and Sperm oils are illuminating oils with high flashing points. Nujol, Stanolax and Russian oil are heavy distillates rich in paraffin. Vaseline, petroleum ointment and cosmoline are paraffin residues. Purified paraffin is used as an adulterant in candy, for water-proofing and for electrical insulation. Crude petroleum is employed as a fuel and is sprinkled on roads to prevent the rise of dust. Tar and asphalt are used in making roofing, in water-proofing, as a binder in road making, in the manufacture of coal briquets and for many other purposes.

COMPOSITION AND PROPERTIES OF NATURAL GAS

Natural gases consist mainly of the lightest components of the marsh gas series, i.e., the lowest members of the series composing petroleum, mixed with smaller quantities of the higher members and small portions of CO_2, CO, and O. A few contain in addition notable quantities of hydrogen, all of them more or less nitrogen, some of them small quantities of hydrogen sulphide and a few comparatively large proportions of helium.

Helium has been obtained most abundantly from some of the gases in southern Kansas, Arkansas, northern Texas,[7] and Oklahoma. It is extracted for use in observation balloons and dirigibles. Noteworthy proportions of helium have been found only in gas of high nitrogen content, though there are some high-nitrogen gases that contain only traces of helium.

[7] Rogers, G. S., "Helium-bearing Natural Gas," U. S. Geol. Sur., *Prof. Paper*, 121, 1921.

Gas that escapes from oil wells, "casing head gas," may contain considerable quantities of ethane, propane and butane. Some of these together with some of the vaporized heavier components of the petroleum may be separated from the lighter fractions and extracted as gasoline. In 1927 about $136,000,000 worth of gasoline was extracted from gas.

TABLE XIII.—ANALYSES OF SOME NATURAL GASES

	CH_4	C_2H_6	CO_2	CO	O	N	H	He	H_2S
Iola, Kans.	94.50	...	..	..	.23	5.08	...	.183	..
Dexter, Kans.	14.85	.41	..	..	.20	82.70	...	1.84	..
Stockton, Calif.	62.93	...	.50	Tr.	.70	24.36	11.51	Und.	..
Big Injun, W. Va.	80.94	14.60	..	.40	.20	3.46	Tr.	Und.	..
Findlay, Ohio	92.61	...	.26	.50	.34	3.61	2.18	...	.20
Pipe Line, Petrolia, Texas	51.10	10.20	..	..	..	38.00	...	.966	..

A comparison of the composition of natural and manufactured gases shows that they are markedly different.

TABLE XIV.—ANALYSES OF NATURAL AND MANUFACTURED GASES[8]

	Pa. and W. Va.	*Kansas*	*Coal Gas*	*Water Gas*	*Producer Gas*
CH_4	80.85	93.65	40.00	2.00	2.05
Other hydrocarbons	14.00	.25	4.00	.00	.04
N	4.60	4.80	2.05	2.00	56.26
CO_2	.05	.30	.45	4.00	2.60
CO	.40	1.00	6.00	45.00	27.00
H	.10	.00	46.00	45.00	12.00
H_2S	.00	.00	.00	.00	.00
O	Tr.	.00	1.50	1.50	.05
B.T.U. per 1,000 cu. ft.	1,145,000.00	1,100,000.00	750,000.00	350,000.00	155,000.00

[8] Ries, H., *Econ. Geology*, fifth edition, New York, p. 79, 1925.

MODES OF OCCURRENCE OF OIL AND GAS

Reservoirs.—Commercial oils are usually found in "sands" or "limes."

Sands are more or less porous sandstones, conglomerates or shales from which the oil is prevented from escaping by impervious, or nearly impervious, material.

Limes are porous limestones. They are often magnesian.

The oil exists in the reservoirs in the same way as does artesian water, i.e., in caves, cracks or solution cavities and in the voids between the rock components.

The quantity of oil in a porous bed is easily estimated if we know the pore space of the bed, provided the bed is saturated. If a porosity of 20% is assumed, 100 cubic feet of sand will contain 20 cubic feet oil, therefore under an acre of flat-lying beds there will be in every 100-foot thickness of the sand 43,560 (square feet in acre) $\times$ 20 (cubic feet of oil in column with 1 square foot base) $\times$ 7.5 (gallons, per cubic feet) $\div$ 42 (gallons in barrel) = 155,535 barrels.

The "saturation of a sand" is the percentage by volume occupied by the oil when the pores of the reservoir are completely filled. In the above illustration saturation is 20%.

But since the saturation depends upon temperature, rock pressures, etc., as well as upon porosity, it is rarely ascertained. The United States Geological Survey in its calculations estimates the saturation at 10%. But, of course, not all of this is recoverable any more than in the case of water. Usually less than 30% of the oil contained in sand is recovered. Washburne estimates that different sands of the Midway district, in California will yield from 32 to 1,020 barrels per acre-foot.

The major part of the oil and gas of the world occurs in sedimentary rock beds that are the reservoirs in which the material is accumulated. Originally the beds were horizontal or nearly so, possessing a slight initial dip seaward corresponding approximately to the slope of the

bottom on which they were deposited. When in this condition the oil and the water that is usually associated with it are uniformly distributed through the bed, the former occurring perhaps as a thin layer on top, but nowhere in sufficient quantity to furnish a continuous supply to a well.

When the rocks become tilted, however, the gas and oil, being lighter than the water, migrate up the dip until they meet some obstruction, and there accumulate with the gas above the oil, or, if the rocks are folded, the oil occupies portions of the arches above the water, the gas, if present, occupying still higher portions.

Thus the distribution of the oil and gas is determined largely by the structural attitudes of the rocks in which they occur, and the position of the water level in the reservoir. If it is above or near the top of a reservoir in folded rocks the oil will be near the crest of a fold; if the water is well down in the reservoir the oil will be part way down; if there is no water in the reservoir the oil will be near the bottoms of synclines.

STRUCTURAL RELATIONS [9]

Anticlines.—In folds where the arch is upward in a gentle anticline the oil forms a layer at or near its top, if water is present, and is underlain by the water (Fig. 22). Gas, if present, occupies the apex of the arch, followed downward by a layer of oil and below this by water. In the first case wells strike the oil if drilled at the top of the anticline, in the second case if drilled in a zone extending ring-like around its apex and at a greater or less distance from its top, depending upon the quantity of gas present, and the difference in the dip of the beds on its opposite limbs [10] (Fig. 26). This is the anticlinal theory which

[9] For a detailed discussion of structures favorable as traps for oil and gas accumulation, see Day, D. T., and others, *Handbook of Petroleum Industry.* New York, 1922.

[10] The oil extends farther down the slope with the gentlest dip.

was the first generalization of value that led to the discovery of oil pools.[11]

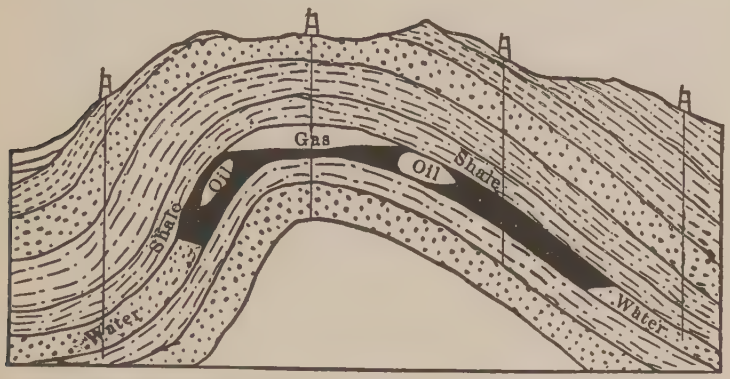


FIG. 22.—Cross-section illustrating ideal relations of gas, oil and water in anticlines as originally suggested by I. C. White.

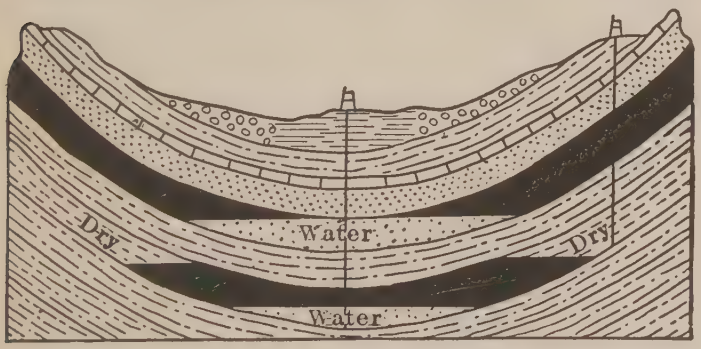


FIG. 23.—Cross-section illustrating conditions favoring the occurrence of oil in synclines. (*After Hager, Practical Oil Geology, McGraw-Hill Book Co., N. Y.*)

As information has accumulated the anticlinal theory has been modified until at present it is recognized that each district is governed by its own laws, depending upon

[11] Campbell, M. R., "Historical Review of Theories by American Geologists to Account for the Origin and Accumulation of Oil," *Econ. Geol.*, Vol. 6, pp. 363–395, 1911; Munn, J. J., "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," *Econ. Geol.*, Vol. 4, pp. 141–157, 509–529, 1909, and discussion by F. G. Clapp, *Econ. Geol.*, Vol. 4, pp. 565–570, 1909.

the peculiarities of its structure and the physical character of the sands or limes in which the oil occurs.

Synclines.—One of the most marked departures from the anticlinal positions of pools occurs when the petroliferous rocks contain no water. In dry rocks the oil is found in the bottoms of synclines.[12] Whether in arches

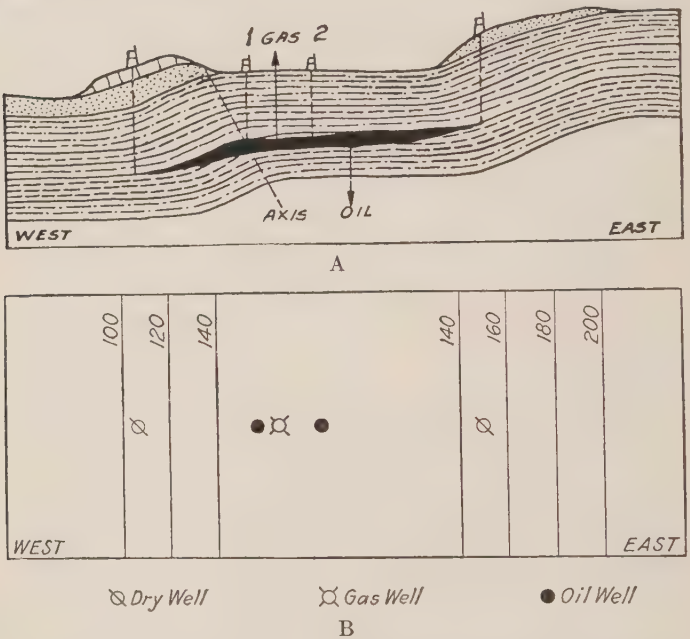


FIG. 24.—Cross-section of oil producing terrace (A) and map with 20 foot contours on oil horizon (B). (*After Hager, Practical Oil Geology.*)

or basins its distribution is such as though determined by gravity. The oil is pulled downward by gravity; but in one case it rests upon the bottom of the porous sand and in the other upon a layer of water which occupies the lower parts of the porous bed (Fig. 23).

Terraces.—Where the oil-bearing rocks are fine-grained,

[12] Reeves, Frank, "The Absence of Water in Certain Sandstones of the Appalachian Oil Fields," *Econ. Geol.*, Vol. 12, pp. 354–378, 1917, and discussion by E. W. Shaw, *Econ. Geol.*, Vol. 12, pp. 610–628, 1917.

or otherwise have a texture which results in high frictional resistance to moving oil, or where the dips are very low, the migration of the oil may be arrested before it reaches the upper portions of arches. It may be caught under those portions of the limbs of the folds where the dips are very low, and consequently where the structure is terrace-like. Indeed, in many cases the most favorable sites for pools are on the flat portions of folds, and on those limbs of folds that show the lower dips (see Figs. 24 and 25).

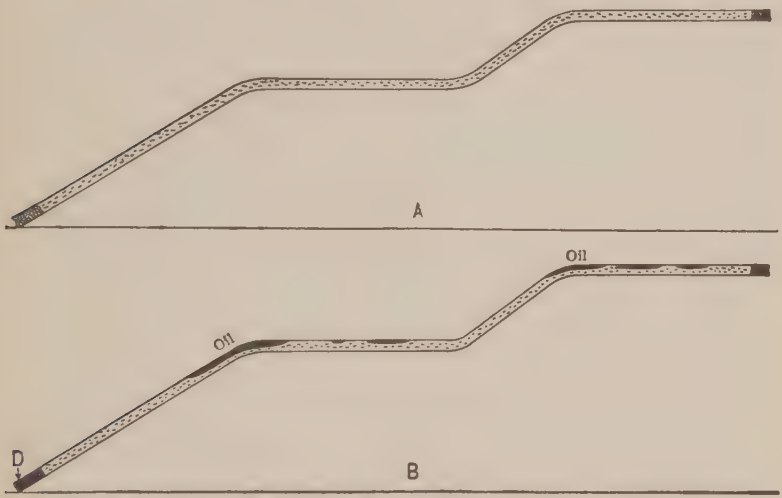


FIG. 25.—Experiment illustrating accumulation of oil on terraces. A, Bent tube containing clean sand saturated with oil and filled with acidulated water. B, Distribution of oil in the same tube a short time after dolomite was introduced at D. Gas generated by the dolomite caused the oil to rise and collect at the bends and in the flat parts of the tube. (*After Emmons, General Economic Geology, McGraw-Hill Book Co., N. Y.*)

Where folds are very broad and the dips over wide areas are monoclinal, pools may occur at those places where there are sudden changes in the dip, provided there is a sufficiently large area down the dip from which the oil may have come,[13] and also where the oil-bearing bed has been

[13] Clapp, F. G., "Notes on the Occurrence of Oil and Gas Accumulations in Formations Having Monoclinal Dips," *Econ. Geol.*, Vol. 6, pp. 1–12, 1911.

pinched on the up-dip side or has become clogged with clay or other material that may fill its pores.

Domes.—In many places bedded rocks are folded into domes, with quaquaversal dips. These are anticlines folded transversely into cross anticlines. As in the case of simple anticlines the oil will be found near the tops of the domes, in a ring around their tops or on terraces—the

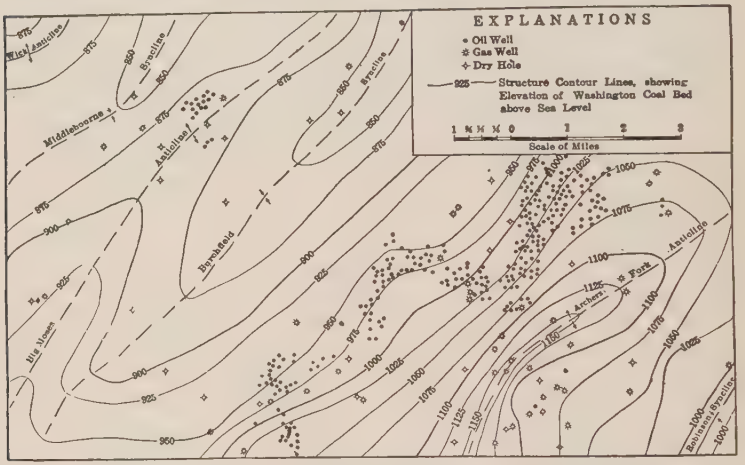


FIG. 26.—Structural map of a typical oil and gas field in W. Virginia. The gas fields are at the tops of the anticlines. The oil fields are on their limbs. Dry holes are in the synclines. (*After White and Henwen, W. Va. Geol. Sur., 1911.*)

distribution being determined by the same conditions that determine the distribution in the simple anticlines (Fig. 26).

There are other kinds of domes, however, in which oil sometimes accumulates which are not produced by the cross-folding of anticlines. Among these are the salt domes of the Coastal Plain of Texas and Louisiana and the volcanic necks in Mexico.

Salt domes.—The salt domes are stock-like masses of rock salt that have been forced up beneath sedimentary beds, doming them and shattering their edges (Fig. 27). The salt is usually covered by anhydrite and gypsum, fol-

lowed above by a cavernous calcite the openings in which are often filled with sulphur crystals. The oil and gas in these domes are in the deeply buried, steeply dipping sand lenses on the flanks of the domes, in the calcite masses that occur on its top, forming a cap over the salt, and in sand lenses lying just above the cap (Fig. 28).

There has been much discussion as to the origin of the salt domes. Clapp [14] declared in 1912 that the most acceptable theory accounted for the domes as due to the rise of hot salt water forced upward under artesian pressure at

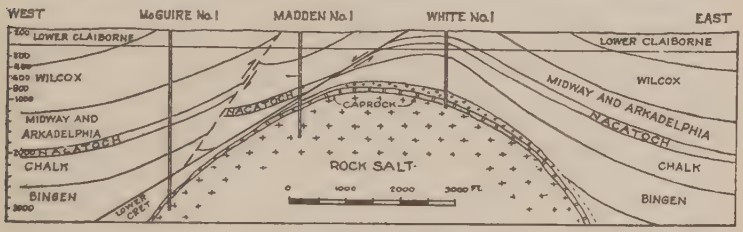


FIG. 27.—Cross-section of Arcadia salt dome, Louisiana. Illustrating relation of the cap rock to the salt plug. The rock beds are Upper Cretaceous and Eocene. (*After W. C. Spooner: Interior salt domes of Louisiana: Geol. of Salt Dome Oil Fields, p. 280. Pub. by Amer. Assoc. Petrol. Geologists, 1926.*)

weak places, where faults cross a series of nearly horizontal rocks, and the resulting precipitation of the salt as the solution neared the surface where pressure and temperature were reduced. The solidification of the salt was attended by crystallization, the power of which was so great that the overlying rocks were raised, forming the domes.[15]

Another theory ascribed the domes to the presence [16] of

[14] Clapp, F. G., "Occurrence of Oil and Gas Deposits Associated with Quaquaversal Structure," *Econ. Geol.*, Vol. 7, pp. 367–377, 1912.

[15] Harris, G. D., "The Geological Occurrence of Rock Salt in Louisiana and East Texas," *Econ. Geol.*, Vol. 4, pp. 21–23, 1909.

[16] Hager, Lee, "The Mounds of the Southern Oil-fields," *Eng. and Min. Jour.*, Vol. 78, pp. 137–139, 180–183, 1904, and discussion by DeGolyer, E. L., "The Theories of Volcanic Origin of Salt Domes," Am. Inst. Min. Eng., *Bull.* 137, p. 987, 1918.

volcanic plugs or laccolites that lifted the rocks at a time which was so recent that erosion has not yet uncovered them. This theory was supported by the existence of volcanic plugs in the Coastal Plain of Mexico.[17]

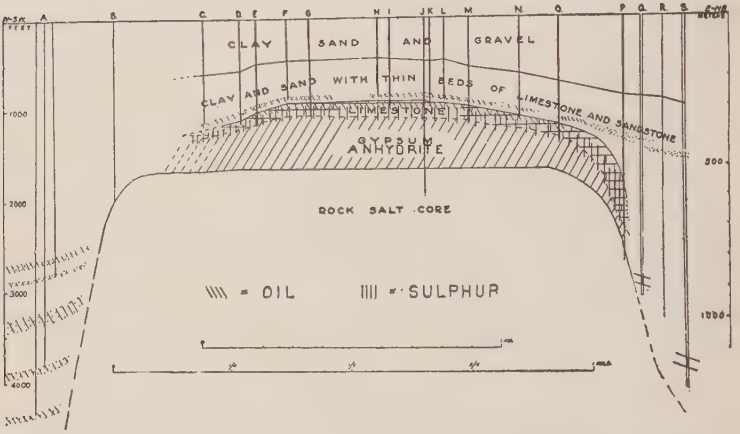


FIG. 28.—East and west section through the Spindletop salt dome, showing the occurrence of the oil and of the sulphur. The section and the occurrence of the oil are essentially those of the Spindletop salt dome, but the cap has been modified slightly in order to represent the occurrence of the sulphur, as Spindletop is not a sulphur dome. Wells A= the 3,000–5,000-foot (900–1,500-meter) wells producing from the lateral sands of the southwest flank of Spindletop. Wells C, F, H, L=shallow oil wells producing from the super-cap sands. Wells D, I, K, N=oil wells producing from the calcite of the cap. Wells E, G, M, O, P represent sulphur wells. Wells Q, R, S=actual dry holes on the east side of Spindletop. (*After D. C. Barton, Univ. of Texas Bull. 2801.*)

The theory now generally accepted accounts for the salt domes as due to the intrusion of the salt *en masse*. According to this theory, the salt plugs are off-shoots of bedded salt deposits forced into the domed area by pressure in a semi-plastic condition,[18] just as the "salt anti-

[17] Moore, R. C., and others, *Geology of Salt Dome Oil Fields*. A Symposium. Am. Assoc. Petrol Geol. Tulsa, Okla., 1926.

[18] Rogers, G. S., "Intrusive Origin of the Gulf-Coast Salt Domes," *Econ. Geol.*, Vol. 13, pp. 447–485, 1918.

clines" and "salt stocks" of the Zechstein (Upper Permian) were formed in Germany.[19]

Recent experiments [20] seem to show that this explanation is a reasonable one (see Figs. 29 and 30).

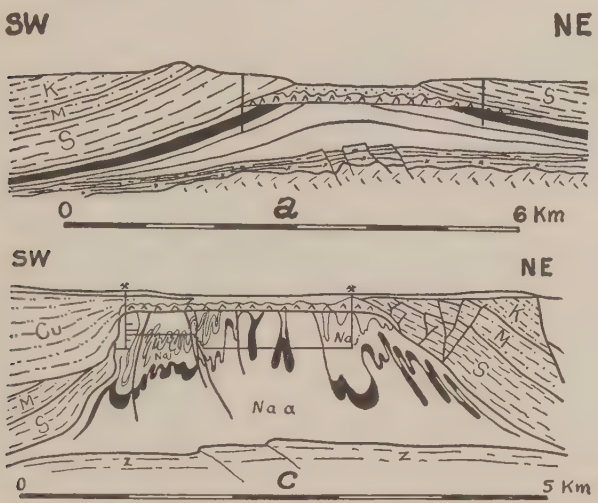


FIG. 29.—Cross sections of salt dome ridges: a, Stassfurt type ridge, and c, the Benthe salt dome, a Hanoverian type salt dome. (*After Schlafke, Stille, Seidl.*) Cu = Lower Cretaceous, K = Keuper, M = Muschelkalk, S = Buntsandstein, Na-j = "Younger" Salt Series, Na-a = "Older" Salt Series, Z = Lower Zechstein. In fig. a and c the black band represents the "Main" anhydrite; the "Older," or main potash-bearing zone, lying immediately under it. The much-contorted light black lines above the letters "Na-j" in fig. c represent the position of the "Younger" potash-bearing zone of the Hanover District. (*After D. C. Barton, Univ. of Texas Bull. 2801.*)

Volcanic domes.—In Mexico, and possibly a few other places, plugs [21] of basalt and other similar rocks protrude through the sediments of the Coastal Plain upturning them near the contacts and opening cavities in them along

[19] Stille, H., "The Upthrust of the Salt Masses of Germany." Trans. by D. C. Barton: *Geol. of the Salt Dome Oil Fields*, Am. Assoc. Petrol. Geol., Tulsa, Okla., pp. 142–166, 1926.

[20] Torrey, P. D., and Fralich, C. E., "An Experimental Study of the Origin of Salt Domes," *Jour. of Geol.*, Vol. 34, pp. 224–234, 1926.

[21] Clapp, F. G., *Econ. Geol.*, Vol. 6, pp. 377–380, 1911.

their bedding planes and thus furnishing reservoirs in which oil travelling up-dip was caught. Seepages occur at the contact, but where the porous beds are covered by impervious layers through which the oil cannot escape large deposits are entrapped, and wells put down near the plug often penetrate several oil horizons (Fig. 30).

DeGolyer,[22] however, takes exception to this theory and concludes that the doming antedates the plugs, and that

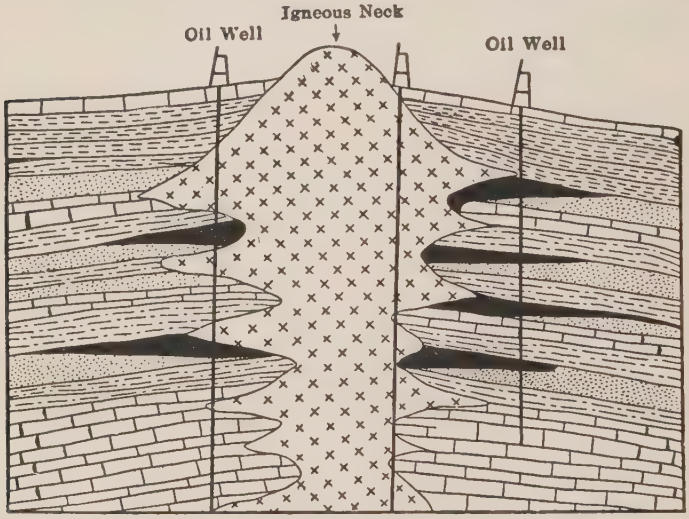


FIG. 30.—Ideal cross-section of volcanic plug and associated oil accumulations. (*After Hager, Practical Oil Geology.*)

the function of the igneous rocks, whether plugs, necks or dikes, has been in providing channels in the contact zones along which the oil could migrate to higher levels.

Lenses.—The occurrence of oil and gas in lenses is much more common than it was formerly supposed to be. Indeed, much of the new exploration in oil districts is directed toward the discovery of lenses of porous rocks

[22] DeGolyer, E., "The Effect of Igneous Intrusions on the Accumulation of Oil in the Tampico-Tuxpam Region, Mexico," *Econ. Geol.*, Vol. 10, pp. 651–662, 1915.

that have not been penetrated by wells (Fig. 31). All sediments, from the very nature of their method of origin, are lenses; usually, however, these lenses are very long and broad. But in lakes and river courses short or narrow

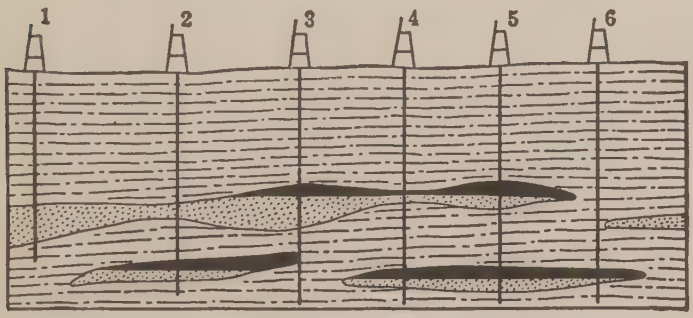


FIG. 31.—Figure illustrating storage of oil in sand lenses. (*After Hager, Practical Oil Geology.*)

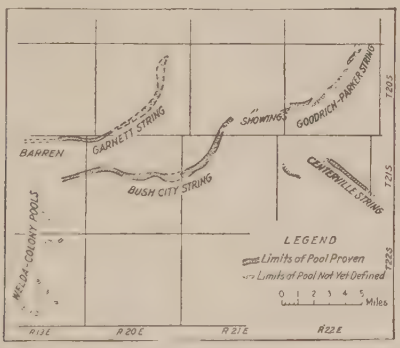


FIG. 32.—Map of Shoe-string lenses in Kansas. (*After Rich, Bull. Amer. Asso. Petrol. Geol., Vol. X, 1926.*)

lenses are produced and these if buried in finer grained material may become reservoirs for oil storage.[23] They are sometimes referred to as "shoe-string sands" (Fig. 32). Sand lenses are common in glacial deposits, and most of

[23] Rich, J. L., "Further Observations on Shoe-string Oil Pools of Eastern Kansas," Am. Assoc. Petrol. Geol. *Bull.*, Vol. 10, No. 6, pp. 568–580, 1926.

the oil and gas obtained from such deposits comes from them.

Faults.—An oil-bearing bed in a monoclinal series or on the limb of a fold, which would otherwise outcrop at the surface and thus lose its oil, may be sealed by a fault filled

Fig. 33.—Sketch showing reservoir formed by faulting of oil sand against impervious rock. (*After Emmons, General Economic Geology.*)

with impervious gouge or paraffin. The oil and gas migrating upward would there accumulate down-dip from the fault, and if the bed were shattered where faulted a large pool might result (Fig. 33).

In other places, an oil-bearing bed may be faulted against a relatively impervious bed, which would stop the

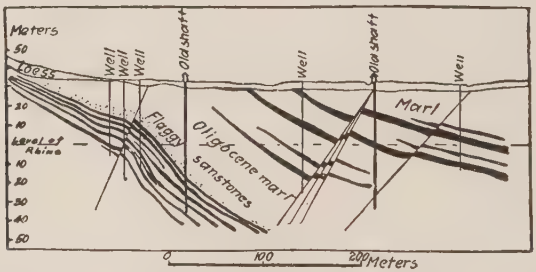


Fig. 34.—Geologic cross-section through Schwabweiler Field, Alsace. Black beds are petroliferous. The producing beds are lenses on faulted monoclines. (*After Audreae, in Emmons, General Economic Geology, 1st Ed., p. 188.*)

circulation of the oil and cause the accumulation of a pool (Fig. 34).

Unconformities.—An unconformity may destroy a structure that would otherwise house an oil pool or it may furnish a reservoir for its occupancy.

If the top of an anticline has been eroded and unconformably covered by rocks that are not impervious to oil any bed in the anticline that might otherwise be oil-bearing might drain to the surface and thus the accumulation of oil in it would be prevented (Fig. 35). If, however, the covering beds are impervious any porous member on the limbs of the fold may furnish favorable sites for pools.

Moreover, the loose material that usually covers a surface that has been eroded by terrestrial agencies may,

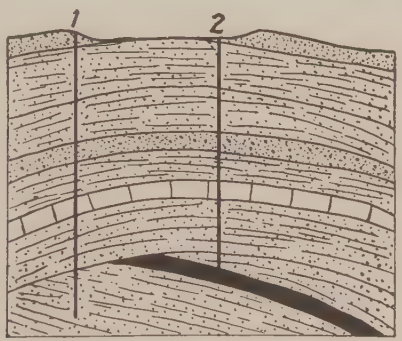


FIG. 35.—Cross-section showing how an unconformity may furnish a favorable condition for oil storage in an underlying formation. (*After Hager, Practical Oil Geology.*)

when buried, become a repository for oil migrating from the surrounding rocks (Fig. 36). A few oil pools of this character have been found in Illinois[23a] (Fig. 37), and Texas (Fig. 37*a*).

Thus unconformities in an oil-bearing series of rocks often complicate the conditions to such an extent that it is difficult, if not impossible, to prophesy where an accumulation of oil may exist.[24]

[23a] Savage, T. E., "Geologic Structure of Canton and Avon Quadrangles," Ill. State Geol. Sur., *Bull.* 33, pp. 95–96, 1916.

[24] See Lahee, F. H., "Geologic Factors in Oil Prospecting," *Econ. Geol.*, Vol. 14, pp. 480–490, 1919.

FIG. 36.—Wall of road-cut near Canton, Ga., showing deposit of residual material produced by weathering, lying on the truncated layers of nearly vertical schists. If covered by impervious beds the residual layer might serve as an oil reservoir.

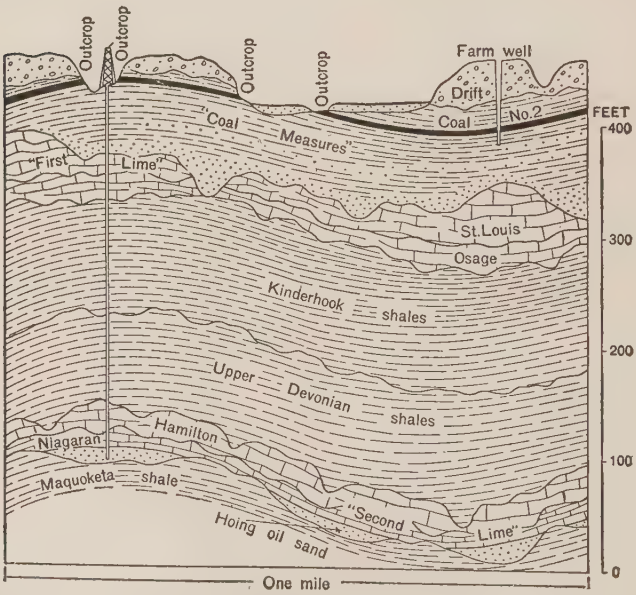


FIG. 37.—Diagram showing how deposits in depressions on an old erosion surface may furnish reservoirs for oil storage. Avon-Canton region, Illinois. (*After T. E. Savage, Ill. State Geol. Sur., Year Book, 1915.*)

Unconformities above limestones are particularly conducive to oil accumulation. All unconformities are erosional phenomena. The underlying rock must have been at the surface before the unconformity was formed and must have been subjected to weathering. If the underlying rock was a limestone it must have suffered the same

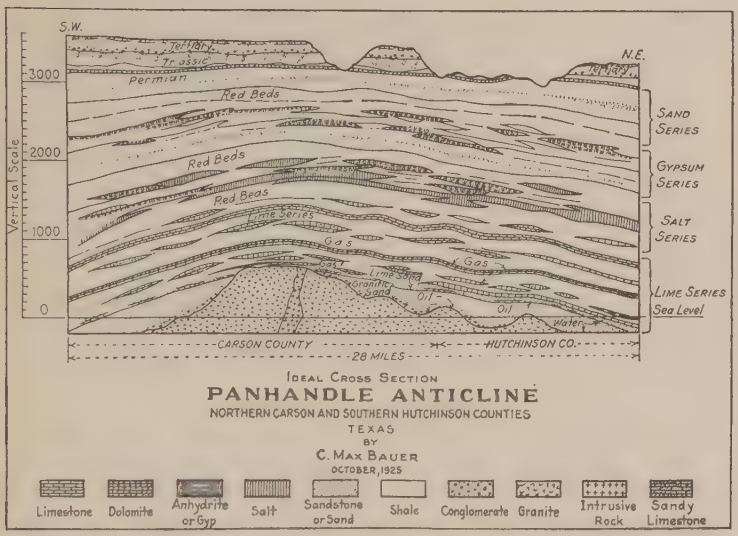


FIG. 37a.—Ideal cross-section of the Panhandle Anticline, Carson and Hutchinson Counties, Texas, showing occurrences of oil in the debris above the unconformity between a series of sedimentary beds and an underlying granite. (*After C. Max Bauer, Bull. Am. Assoc. Petrol. Geol., Vol. 10, pp. 744–746, 1926.*)

kinds of weathering as do limestones now at the surface. It may have become porous through the solution of some of its constituents and to have had developed in it porosity, caves, underground passages, etc. If such a weathered limestone is overlain by an impervious bed the outlets of the openings would be sealed, thus furnishing cavities in the rock which would afford excellent sites for the storage of gas and oil. Many reservoirs in Ohio

and west Texas are believed to be in limestones under unconformities.[25]

Buried topography.—In regions of flat or gently dipping beds, the topography of the surfaces that form the basement on which sediments were laid down may have an important influence in producing structures in which oil may be stored. Above buried hills, the overlying beds, which are horizontal elsewhere, are often bowed up and thus furnish structures that are favorable traps for moving oil. These favorable structures may be anticlines or they may be the upturned edges of layers that never covered the hills. Powers [26] cites Cushing in Oklahoma, and Amarillo in Texas as illustrations of places where the underlying hills were not covered by the oil horizons. Here the oil is on the flanks of the hills and not on their summits (Fig. 38). He concludes, therefore, that dry holes which encounter an unconformity on the top of such a structure do not condemn the flanks.

The upward bowing of the beds of a normally horizontal series on the flanks of a buried projection has not been satisfactorily explained, but Blackwelder [27] thinks it due to the difference in the amount of settling above and around the elevation as the sediments consolidated.[28]

Petrography of reservoir rocks.—It is evident that the oil existing in rocks must occupy openings in the rock masses. Many rocks like sandstones are inherently porous because of their nature. Others, like granite, are

[25] Howard, W. V., "A Classification of Limestone Reservoirs." Am. Assoc. Petrol. Geol., *Bull.*, Vol. 12, pp. 1153–1161, 1928.

[26] Powers, S., "Reflected Buried Hills and Their Importance in Petroleum Geology," *Econ. Geol.*, Vol. 17, pp. 233–259, 1922, and discussion by G. M. Ruby, *Econ. Geol.*, Vol. 18, pp. 93–96, 1923.

[27] Blackwelder, Eliot, "The Origin of the Central Kansas Oil Domes," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 4, pp. 89–94, 1920.

[28] Descriptions of the structures of many typical American oil fields will be found in a recent publication *Structure of Typical American Oil-fields, a symposium on the relation of oil accumulation to structure.* Vols. I and II, 1929, Am. Assoc. Petrol. Geol., Tulsa, Okla., 1929.

not inherently porous, except to a very slight extent, but they may have fissures produced in them by deformational stresses. Of course, all rocks containing pore space may store oil under favorable conditions, but some rocks may

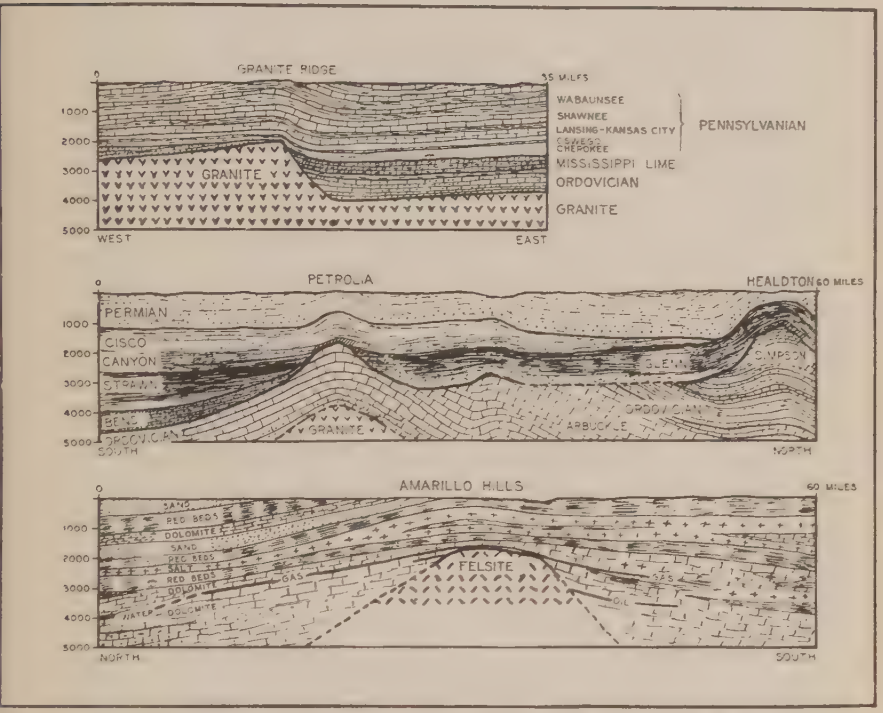


FIG. 38.—Cross-section of Granite Ridge, Kan.: Petrolia and Healton, Oklahoma and Texas, and Amarillo, Texas, showing effects of buried hills on overlying bedded rocks. (*After Powers, Economic Geology, Vol. 17.*)

have openings induced in them by forces which, acting upon other rocks, would close spaces already existing. Thus a hard shale under stress might become shattered and furnish a collecting field for oil, whereas, a soft shale under similar stresses might be molded and sheared and become more impervious than it was originally. Formerly

only sands and limestone were regarded as favorable reservoir rocks, but it is now coming to be recognized that any rock may become the repository of oil and gas provided it contains openings of any kind that do not drain readily. Thus igneous rocks may be oil-bearers if they are amygdaloidal or if they contain induced openings like those occurring in granites that furnish artesian water. In the Lytton Springs oil field in Texas most of the oil comes from "serpentine." [29] It has now become as important, therefore, for the oil geologists to study the character of the possible reservoir rocks in a district as to study their structural features.[30]

Relation of oil pools to shore lines.—All the explanations proposed to account for the accumulation of oil in structural traps are based on the belief that the oil moves into them as the result of some push or pull applied to it. In other words, on the belief that it migrates. A few geologists believe that the migration was through short distances only, and that the pools are near the source of supply of the oil. It is presumable that if petroleum is of organic origin the materials from which it was made were laid down with the rocks that were being deposited at the same time. It is well known that the most favorable conditions for deposition are near shore lines and that it is near old coasts that the oil-making substances must have been laid down, and that it is here that the oil must have been formed.[31] If it did not migrate far, it must

[29] Collingwood, D. M., and Rettger, R. E., "The Lytton Springs Oil Field, Caldwell County, Texas," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 10, pp. 953–975, 1926.

[30] Lauer, A.W., "The Petrology of Reservoir Rocks and Its Influence on the Accumulation of Petroleum," *Econ. Geol.*, Vol. 12, pp. 435–465, 1917, and discussion by W. F. Jones, E. W. Shaw and G. S. Rogers in *Econ. Geol.*, Vol. 13, pp. 147–149, 207–222 and 316–324, 1918.

[31] Jones, W. F., "The Relation of Oil Pools to Ancient Shore Lines," *Econ. Geol.*, Vol. 15, pp. 81–87, 1920, and discussion by F. H. Lahee in *Econ. Geol.*, Vol. 15, pp. 350–354, 1920.

exist in belts approximately parallel to old shore lines. Jones declares that in his opinion "there is a great deal of evidence to show that the individual oil pools of Appalachian and Mid-Continent regions do not conform in general to structural deformations * * * * but they bear a close relationship to the configuration of the ancient coast lines in each case." According to this view pools occur in alignment parallel to coastal lagoonal areas, with successive lines of pools, corresponding to successive shore lines, the larger pools being elongated parallel to them.

Aside from the larger questions with reference to the sites at which the oil was originally produced there is another consideration with reference to the relation of oil pools to shore lines that is of importance to explorers. The normal distribution of sediments off shore is pebble deposits, sand, mud and limestone. The sands grade shoreward into conglomerates and seaward into shales. While deposition is taking place, the shore line, and with it the sandy, muddy and limey belts, may alternately advance and retreat, thus producing a stratified series which is repeated several times, making correlation difficult, and the missing of oil pools very possible.

Oil brines.—Gas and salt water are nearly always closely associated with oil, the water being beneath and the gas above. In some places only oil and gas occur and in others oil and water. In most places the water is genuine brine, containing so much salt that it has been thought by most geologists to be connate, but Richardson[32] believes that if the water associated with oil in the Devonian beds in Butler County, Penna., represents portions of the old Devonian ocean it must certainly have changed markedly in composition since it has been in the rocks. He quotes analyses of the waters from two oil horizons

[32] Richardson, G. B., "Note on Appalachian Oil-field Brines," *Econ. Geol.*, Vol. 12, pp. 39–41, 1917.

showing their salinity to be over 13% and 26%, whereas the salinity of the water of the present ocean is only 4%. He is inclined to think that the brines result from prolonged leaching of the rocks through which they have passed. The high content of salt in the two brines analysed, he thinks, may have come from the Salina formation, which is known to contain rock salt in the neighborhood of the wells furnishing the brines.

The waters characteristic of oil-bearing rocks are alkaline-sulphide waters. Palmer [33] concludes that they are derived from alkaline carbonate water, which is the normal deep ground water, by absorption from the latter of a volatile sulphur compound emanating from the oil. Hence, it has been inferred that it may be possible to identify oil horizons by analysing the water tapped during drilling operations.

Rock pressure.—Since gas that exists in the earth must be under pressure, when opportunity offers it escapes with violence, carrying with it any oil and water that may be associated with it, often delivering these at the surface through a flowing well. As the gas escapes the pressure is relieved and the released gas may not be able to carry the fluids to the surface. The well then becomes a pumping well.

The maximum pressure developed when the well is closed is the rock pressure.

In 1885 the rock pressure at Findlay, Ohio, was 450 lbs. per square inch. In 1886 it was 400 lbs., in 1889 it had fallen to 250 lbs., and in 1890 it had dropped to 190 lbs. Some West Virginia wells show a rock pressure of 2,000 lbs. and some Mexican wells probably more.

It was first thought [34] that the rock pressure is the same

[33] Palmer, Chase, "Calif. Oil-field Waters," *Econ. Geol.*, Vol. 19, pp. 623–635, 1924.

[34] Orton, Edw., Ohio Geol. Survey, Vol. 6, pp. 60–100, 1888, and Smithsonian Inst., *Ann. Rep.*, 1891, pp. 155–162, 1893.

as that of a column of water whose height is equal to the difference in elevation between the water table and the oil or gas-bearing stratum.

A depth of 1,000 feet corresponds to a hydrostatic pressure of 432 lbs. per square inch, a depth of 2,000 feet to a pressure of 864 lbs., and a depth of 3,000 feet to a pressure of 1,296 lbs. Since, however, many shallow wells show a pressure much greater than can be accounted for by their depth, some deep wells show small pressures, and, moreover, no near relationship can be shown to exist between the levels of wells in a single field and their depths, and, further, the presence or absence of water in the producing sands seem to have little influence on the pressure, it is now thought that the rock pressure is due to the expansive force of gas imprisoned by some other agency than the mere load of overlying water. It may be that the gas was generated faster than it could escape through nearly impervious beds and thus acquired a pressure.

THEORIES OF ORIGIN

The theories proposed to account for the origin of petroleum and the associated gas have been of three principal types.

1. The chemical theory, of which the most noted is Mendelejeff's carbide theory.
2. The volcanic theory, and
3. The organic theory.

Chemical theory.—According to the carbide theory water percolated downward through the earth's crust, came in contact with iron carbides at a high temperature, and formed acetylene, which, when subjected to different degrees of heat and pressure, gave rise to condension products which constitute the petroleum.

It is possible that the earth's interior is made up of metallic iron and iron carbide. It is not probable, how-

ever, that water percolating from the surface could reach it. Moreover, if oil were so formed there is no reason why it should not exist in old porous rocks like many of the ancient schists, and yet it is found only in sedimentary rocks or only locally in other rocks at places into which it might readily have entered from neighboring sediments.[35]

Volcanic theory.—The volcanic theory is advocated by only a few geologists at the present time.

It is asserted by those who accept this theory that vegetable or animal remains entombed in the rocks cannot have formed oil because they must have been decomposed before they were entirely sealed and their decomposition products must have escaped. Further, they call attention to the fact that marsh gas and other hydrocarbons are among the products of volcanic action—at any rate that they escape from volcanic vents. Moreover, they declare that oil and gas fields are found mainly along faulted and fissured zones in the earth's crust, that oil, gas and bituminous matter are not indigenous to the rocks in which they are found and that the density of the rocks precludes any possibility of their having been upbowed by any force but volcanic pressure.

Only the first and second of these arguments have much force. We know that oil may occur in areas undisturbed by volcanic activity, and that the rock pressure may be the result of the expansive effect of gas. That volcanoes sometimes erupt hydrocarbons is true, but in oil-producing areas where there are no volcanoes these cannot well be the source of the oil. Organic substances are known to yield hydrocarbons on decay under certain conditions,

[35] See also Becker, G. F., "Relations Between Local Magnetic Disturbances and the Genesis of Petroleum," U. S. Geol. Sur., *Bull.* 401, 1909, and Tarr, W. A., "The Lack of Association of the Irregularities of the Lines of Magnetic Declination and the Petroleum Fields," *Econ. Geol.*, Vol. 7, pp. 647–661, 1912.

and it is believed that these conditions exist at many places where organic material was buried. The increase in temperature as oil-producing rocks are approached has been thought by some geologists to be evidence in favor of the volcanic origin of oil, but this increase is so slight, even in regions which are known to be volcanic, that it is ascribed by most geologists to chemical or to physical agencies other than those of volcanic origin,[36] especially since a similar increase is found in rocks underlain by coal.[37]

It is also to be recalled that oil and gas are restricted to sedimentary rocks and never occur in volcanic rocks that are not in such relations with sedimentary rocks that they may not have received their supplies from these.

Finally, the decrease in rock pressure which many wells show during a comparatively short life is not in accordance with the view that the pressure is produced by volcanic forces.[38]

Organic theory.—The organic theory, which is now accepted almost unanimously by oil geologists, was proposed to meet the objections to which all other theories as to the origin of oil are subject. Any theory must suggest not only the original source of the oil and of the gas associated with it, but must explain also the way in which these substances arrived at their present positions and the cause of the variation in the oils of different localities.

The organic theory accounts for the oil and gas as decomposition products of organic matter. There is no

[36] Höfer, H. von, "Temperature in Oil Regions," *Econ. Geol.*, Vol. 7, pp. 536–541, 1912, and DeGolyer, E., "The Significance of Certain Mexican Oil Field Temperatures," *Econ. Geol.*, Vol. 13, pp. 275–301, 1918.

[37] Lindgren, W., *Mineral Deposits*, New York, 1919, pp. 83.

[38] For the most elaborate argument in favor of the volcanic theory see: Costè, E., "Rock Disturbances Theory of Petroleum Emanations *vs.* The Anticlinal or Structural Theory of Petroleum Accumulations: Am. Inst. Min. Eng., *Trans.*, Vol. 48, pp. 504–520, 1915, and *Trans.*, Vol. 35, pp. 288–297, 1905.

agreement among the advocates of this theory, however, as to the kind of organisms that yielded the oil or the relation of its present position to the place at which the organisms were deposited.

The most important phases of the theory ascribe the origin of oil and gas to:

A. Animal matter
   a. Molluscs, fish, etc.
   b. Foraminifera
B. Vegetable matter
   a. Sea weeds
   b. Land plants in swamps
   c. Diatoms and algæ
   d. Lignite and coal

The animal theories are fully competent to explain the occurrence of commercial oil fields, but in order to account for the existence of paraffin, asphalt and mixed oils in different fields it seems necessary to assume mixtures of vegetable and animal matter in different proportions as sources of the oil.

It has been stated by Engler that the catch of herring in the North Sea alone during 1,300 years would be sufficient to yield all the oil that has been produced in Galicia, and yet this is but a small part of the herring that have lived in the North Sea during this time and an insignificant part of those that have lived in the ocean. Indeed, a recent theory [39] accounts for all the oil of the globe as a result of the decomposition of fish remains. The author of the theory, however, finds it necessary to reconstruct much of geologic history in order to make his theory accord with the facts.

Compounds of substances that are essentially petroleum have been made from both animal and vegetable matter

[39] Macfarlane, J. M., *Fishes, The Source of Petroleum.* New York, 1923. Review in *Econ. Geol.*, Vol. 19, pp. 775–778, 1924.

by destructive distillation [40] under conditions that preclude free access of air. A substance that is essentially a paraffin oil has been made from fish. Oil, petroleum and asphalt have been made from a mixture of fish and wood, and gas and a heavy lubricating oil have been made from vegetable oils.

The presence of diatomaceous shales in the oil measures of California and of vegetable remains in the oil measures of other districts seem to lend support to the view that petroleum, in some instances at least, was derived from vegetable remains. This view is further supported by the fact that in many oil shales the organic constituents which yield oil on distillation are plant remains, and that the greater part consists of spores and other waxy parts of plants [41]—substances which upon decomposition yield not only petroleum-like products [42] but also sulphur compounds. When mixed with animal matter nitrogenous compounds are also generated. Thus, in so far as chemical reactions are concerned, petroleum may well be produced by the distillation of either animal or vegetable matter.

The oils of California are regarded by Anderson [43] as of two major types of which one, the asphaltic type, had its origin mainly in diatoms and other vegetable organisms that occur so abundantly in the shales associated with the oil, and the other, the Ventura type, with an olefin or

[40] Clarke, F. W., "Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 743–744, 1924.

[41] Stadnichenko, T., and White, David, "Some Mother Plants of Petroleum in the Devonian Black Shales," *Econ. Geol.*, Vol. 18, pp. 238–252, 1923.

[42] Experimental work on cannel coal, oil shales and bituminous shales has recently been undertaken (Stadnichenko, T., and White, D., "Microthermal Observations of Some Oil Shales and Other Carbonaceous Rocks," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 10, pp. 860–876, 1926) with the hope of learning the sources of the chemical components of the distillates of carbonaceous deposits, and, by inference, something definite with reference to the origin of petroleum.

[43] Anderson, F. M., "Origin of California Petroleum," Geol. Soc. Am., *Bull.*, Vol. 37, pp. 585–614, 1926.

naphthene base, was derived from foraminifera and other marine animal forms, remains of which are found in the rocks with which this type of oil is associated. Moreover, in many of the oil shales from which paraffin oils have been obtained are minute animal forms, consequently, it is suspected that, in general, asphalt oils are derived from vegetable debris and paraffin and naphthene oils from animal remains. It is possible, however, that the organisms in the rocks associated with oil are not its source, but that the material from which it was made was destroyed by the process that made the oil.[44]

Tolman [45] agrees that the California oil owes its origin largely to diatoms, but he believes that these organisms manufactured the oil during the course of their normal life processes, and that it was not produced by their decay and destructive distillation. Living diatoms and perhaps some algæ secrete oil. When their shells are broken this oil escapes and is forced into the surrounding sediment from which it is squeezed into more porous rock by compression.[46]

Clarke,[47] after examining from a chemist's point of view all the theories that have been proposed to explain the origin of petroleum, concludes: "The organic origin of petroleum * * * seems to be best supported by the geologic relations of the hydrocarbons, which are found in large quantities only in rocks of sedimentary character. Any organic substance which becomes inclosed within the sediments may be a source of petroleum, and when the latter happens to be rich in nitrogen, animal matter was

[44] See J.-I. R. Takahashi, "Preliminary Report on the Origin of California Petroleum," *Econ. Geol.*, Vol. 22, pp. 133–157, 1927.

[45] Tolman, C. F., "Biogenesis of Hydrocarbons by Diatoms," *Econ. Geol.*, Vol. 22, pp. 454–474, 1927.

[46] Becking, L. B., and others. "Diatom 'Epidemics' and Analysis of Diatom Oil," *Econ. Geol.*, Vol. 22, pp. 356–368, 1927.

[47] For an excellent discussion of the different theories on the origin of petroleum, see Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 743–755, 1924.

probably the initial material. There is no evidence to show that any important oil field derived its hydrocarbons from inorganic sources" (p. 755).

It is possible that high-grade paraffin oil is derived from gelatinous plants and asphalt base oil mainly from animal remains. However, if there is as much spore material in plant accumulation as is present in bog head and cannel coals and in many oil shales, there must be much fat and wax present and these may produce the same results as animal fats. It is possible that high temperature and rapid alteration produces a heavy asphalt base oil and that low temperature, high pressure, old age and migration may yield light paraffin oils.

Plant and animal matter may be deposited in muds or slimes in either fresh or salt water. After aërobic bacteria ceased to act upon it, it may have been attacked by anaërobic ones and subjected to slow deoxidation. This process may result in the production of coal or oil, depending upon the composition of the debris, the conditions of its accumulation or deposition, or the extent of microbian action.[48]

Craig,[49] as the result of his experimental work on jet, and certain kinds of cannel coal, in which he finds "compounds akin to petroleum," believes that great pressure out of contact with oxygen may be a sufficient cause of the production of oil from vegetable matter, without the aid of bacterial action. "It has been seen," he writes, "that in jet, lignites and jetonized material the wood has certainly been preserved from decay, and yet not pre-

[48] White, David, Geol. Soc. Am., *Bull.*, Vol. 28, pp. 727–734, 1917. See also Dalton, L. V., "On the Origin of Petroleum," *Econ. Geol.*, Vol. 4, pp. 603–631, 1909, and discussion by R. Zuber, *Econ. Geol.*, Vol. 5, pp. 194–195, 1910, and H. Hofer, Vol. 5, p. 564, 1910. A good summary of the organic theory of the origin of petroleum is to be found in an article by E. Clark in Inst. Petrol. Technologists (London) *Jour.*, Vol. 12, pp. 257–287, 1926.

[49] Craig, E. D. C., "Jet and Jetonized Material," Inst. Petrol. Technologists (London) *Jour.*, Vol. 13, pp. 353–354, 1927.

vented from changing in chemical composition in the direction that would enable it to become the raw material from which petroleum could be formed. It is difficult to conceive of bacteria attacking such jetonized material buried beneath thousands of feet of sedimentary strata and sealed in a natural autoclave. Yet the evidence all points to the probability of petroleum having been formed under these conditions."

CAUSES OF DIFFERENCES IN PETROLEUM

Some of the differences in the great variety of oils occurring at various places are probably to be accounted for (1) by differences in the original organic material deposited, (2) by differences in the physical conditions at the time of formation, affecting the biochemical action of the attacking microbes, (3) by differences in the degree of metamorphism to which the first formed oil was subjected and (4) by differences in the manner and distance of its migration and the consequent difference in the filtration products.[50]

The effects of the first two sets of conditions need no special discussion. It is probable that differences in the material from which the oil was made and differences in the physical conditions under which decomposition was effected must necessarily affect the product, as will also chemical reactions between the products and substances with which it comes in contact.

It is also apparent that differences in the specific gravity of oils are due to the presence or absence of the various lighter components, and this in turn is the result of devolatilization, even if the oils were originally alike in composition. White suggests therefore that the varieties

[50] Mabery, C. F., "The Relations of the Chemical Composition of Petroleum to Its Genesis and Geological Occurrence," *Econ. Geol.*, Vol. 11, pp. 511–527, 1916.

of oil, like the varieties of coal, are due to devolatilization after the biochemical stage of alteration, and that the devolatilization is accomplished by dynamic agencies.

On the assumption that coal and oil are produced from organic matter it was plain to White[51] that the composition of both must have certain features in common and that these features must vary similarly in proportion as the two products are subjected to similar vicissitudes.

He realized that coals vary in response to varying degrees of metamorphism, and, therefore, he conceived the notion that petroleums in the same district must vary in the same way; but that since many of the components of the latter are volatile there is a point in the increasing metamorphism of petroleum where practically all of the characteristic components of this substance will disappear, whereas some constituents of the coal under the same conditions will still remain. He then sought a means of recognizing this point and found that certain varieties of coal, characterized by the possession of less than a certain proportion of volatile materials, indicate a degree of metamorphism which precludes the existence of petroleum.

Carbon-ratios.—The relation between volatile materials and fixed carbon (known as the carbon-ratio) in coal measures the amount of metamorphism to which the coal has been subjected. It is expressed by the fraction $\frac{\text{fc}}{\text{fc} + \text{vol. matter}}$. Lines on the surface in a coal area indicating the positions of points of equal carbon-ratios are called "isovols." By careful investigation it was found that in the districts studied by him where this ratio is over 65 in coal commercial oil pools are rare (Fig. 39). The ratios increase gradually downwards as

[51] White, David, "Some Relations in Origin Between Coal and Petroleum," Wash. Acad. of Sci., *Jour.*, Vol. 5, pp. 189–212, and discussion by R. H. Johnson, *Econ. Geol.*, Vol. 10, pp. 676–679, 1915.

well as toward areas of disturbance and suddenly below unconformities. "If we examine the oils of the U. S.,"

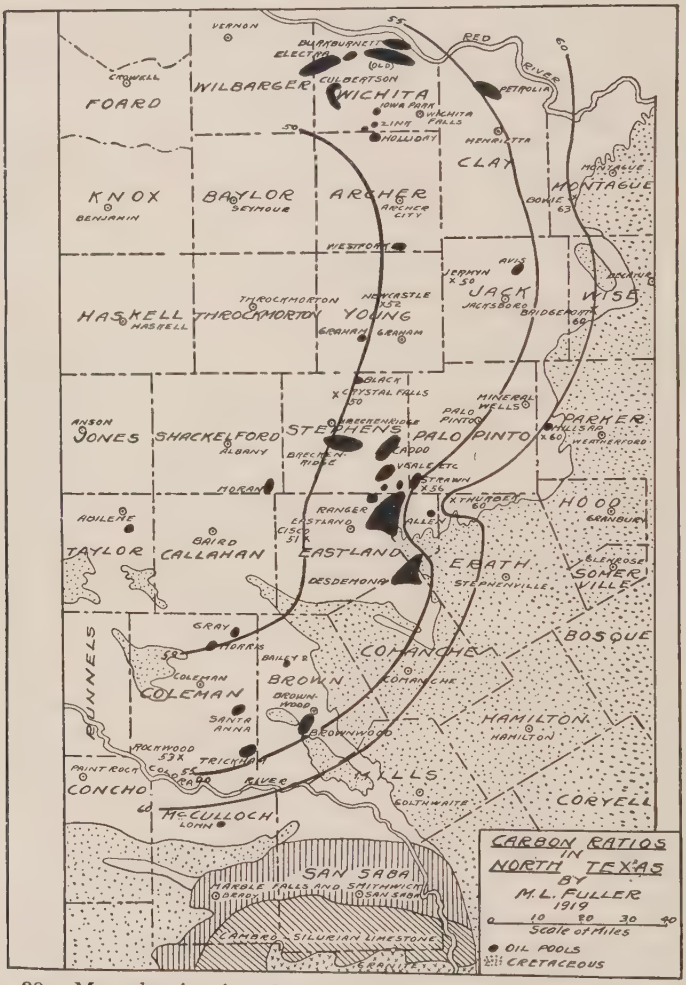


FIG. 39.—Map showing isovols and the relation of oil pools to carbon-ratios of coals in Northern Texas. (*After Fuller, Economic Geol., Vol. 14.*)

writes White, "we find that in the formations and regions in which the carbonaceous detrital deposits (coals) are but

little altered by dynamic influence, the oils are heavy and of low rank, that is, they are high gravity oils. On the other hand, in regions of more advanced alteration of the residual organic debris, the oils are in general of correspondingly higher ranks (lower gravities), the highest degree of alteration of the residues being, in general, noted in the regions of highest rank of oil pools" (p. 203).

Among the conclusions he reaches after comparing the gravities of the oils in different formations and regions with the stages of alteration of the mother rocks and other carbonaceous deposits found in the same formations as the oil pools, or in formations overlying the pools, are the following:

"(1) Petroleum is a product generated in the course of the geodynamic alteration of deposits of organic debris of certain types buried in the sedimentary strata.

(3) In general, it is seen that the lowest rank oils of each type are found in the regions and formations in which the carbonaceous deposits are least altered; that the oils in formations showing greater alteration of the organic debris, as in sub-bituminous coals, are of higher rank, the oils being still more clearly of high rank in the regions and formations of bituminous coals; and that in the regions of still further alteration the oils are still better, the highest rank oils being, on the whole, found in regions where the carbonaceous deposits in the same or in overlying formations have been brought to corresponding higher ranks.

(4) The effect of progressive regional dynamic alteration is marked by a concentration of hydrogen in the distillates and a concentration of carbon in the residual debris (coal, carbonaceous shale, etc.).

(7) In regions where the progressive devolatilization of the organic deposits in any formation has passed a certain point, marked in most provinces by 60–65% of fixed

carbon (pure coal basis) in the associated or overlying coals, commercial oil pools are not present in that formation nor in any other formations normally underlying it, though commercial gas pools may occur in a border zone of higher carbonization. The approximate carbonization limits of the rocks containing or overlying oil pools may be found to vary somewhat in different provinces according to the characters of the original organic debris, the circumstances attending its deposition and the geologic structure.

(8) Wherever the regional alteration of the carbonaceous residues passes the point marked by 65% or perhaps 70% of fixed carbon in the (pure) coals, the light distillates appear, in general, to be gases at rock temperatures. Occluded oils may, in some cases, have escaped volatilization."

In short, White's most important conclusions are that when metamorphism has proceeded to such an extent that the coals in the metamorphosed rocks have been so far devolatilized that their fixed carbon exceeds 65%, or 65% of the pure coal, no oil in quantity may be expected because most of it has been volatilized. Where the metamorphism has not increased the carbon-ratio to this extent in the coal beds, oil may be expected, its amount and quality varying with the degree of metamorphism.

Fuller[52] has outlined the general relations existing between the carbon-ratios and oil expectations in the table on the following page.

By mapping the isovols Fuller has been able to limit the area in which oil is likely to be found in North Texas and Oklahoma (Fig. 39) and thus has been able to diminish materially the necessity for wild-catting. In Oklahoma,

[52] Fuller, M. L., "Relations of Oil to Carbon Ratios of Pennsylvanian Coals in North Texas," *Econ. Geol.*, Vol. 14, pp. 536–542, and "Carbon Ratios in Carboniferous Coals of Oklahoma, and Their Relation to Petroleum," *Econ. Geol.*, Vol. 15, pp. 225–235, 1920.

TABLE XV.—RELATION BETWEEN CARBON-RATIOS AND OIL-POSSIBILITIES

"With lower carbon ratios, oil and gas may be expected, the amount and quality varying with the degree of metamorphism as expressed by the percentage of fixed carbon in coals. For convenience, the relationship is summarized in the following table."

Carbon Ratios (Surface)	*Prevailing Characteristics of Sands*	*Prevailing Water Conditions (In Mixed Formations)*	*Production*
Over 70.....	Hard and tight.	Water usually absent except near surface.	No oil or gas, with rare exceptions.
65–70.....	Tight, with a few porous spots.	Water usually absent below 1,500 feet.	Usually only "shows" or small pockets. No commercial production.
60–65.....	Varied, with porous beds of limited extent.	Water usually absent below 2,500 feet (often below 2,000 feet).	Commercial pools rare, but oil exceptionally high grade when found. Gas wells common, but usually isolated rather than in pools.
55–60.....	Fairly continuous and open.	Water usually absent below 3,000 feet (often below 2,500 feet).	Principal fields of light oils and gas of the world.
50–55.....	Softer, less firmly consolidated, and more continuous and porous.	Water usually absent below 3,000–3,500 feet.	Principal fields of medium oils of Ohio-Indiana and Mid-continental fields.
Under 50.....	Usually unconsolidated and porous throughout.	Sands usually saturated, often with fresh water to all depths reached by wells.	Fields of heavy coastal plain oils and of unconsolidated Tertiary or other formations.

he predicts that oil is not likely to be found in areas east of the 60% isovol. Other geologists have applied the principles developed by White and Fuller to the possible distribution of oil in Alabama,[53] Kentucky,[54] and Illinois[55] and have apparently discovered a few facts that will modify the conclusions which may be derived from the isovols alone. For instance, Russell appears to have found that oil and gas pools may occur in limestones where the regional alteration of the rocks is too high to permit their occurrence in sandstones.

As a result of the study of the relation existing between the character of coals and petroleum it has now been pretty well established that the isovols in some districts have use in predicting the best areas for exploring for oil, but it must be distinctly understood that an isocarb map merely gives an indication of one of the conditions necessary for the occurrence of oil and gas. If other conditions are unfavorable there will, of course, be no production though the isovols are ideal. On the other hand, if the isovols are unfavorable, there may be no oil or gas production even though other favoring conditions be present.

Although it is acknowledged by nearly all oil geologists that the carbon-ratio is of value as an aid in prospecting for oil and gas in some districts, it is not so generally believed that there is a causal connection between stages of metamorphism and their occurrence.

White's statement of the relation existing between the carbon-ratio and the occurrence of petroleum is based on the assumption that the carbon-ratio measures the degree of metamorphism to which the coal has been subjected

[53] Lloyd, S. J., "Relation of Oil to Carbon Rations," *Econ. Geol.*, Vol. 15, pp. 94–96, 1922.

[54] Russell, W. L., "Relation Between Isocarbs and Oil and Gas Production in Kentucky," *Econ. Geol.*, Vol. 20, pp. 249–260, 1925.

[55] Moulton, G. J., "Carbon Ratios and Petroleum in Illinois," Ill. State Geol. Sur., *Report of Investigations*, No. 4, 1925.

and therefore may also indicate the degree of metamorphism suffered by petroliferous substances in the same area. But it is now known that the carbon-ratio is not always a measure of metamorphism and consequently cannot be used as a certain indication of the presence or absence of oil deposits. By many geologists it is thought that the relation between oil and gas occurrences and the carbon-ratio, in some of the districts where it has been noted, is a coincidence which is the result of a combination of circumstances.[56]

In those districts in which coal does not exist, and where naturally carbon-ratios are not available as indicators of the degree of metamorphism to which the rocks have been subjected, it has been proposed to use fine-grained sedimentary beds for this purpose. It has been thought that the degree of metamorphism in silt, mud and clay may be expressed by their specific gravities and the relation between their densities and the carbon-ratio may be as indicated below.[57]

TABLE XVI.—COMPARISON OF SPECIFIC GRAVITY OF FINE SEDIMENTS AND THE CARBON-RATIO

	Sp. Gr.	*Equivalent Carbon-ratio*
Silt	Up to 1.25	Below 50%
Consolidated mud	1.25–1.80	Below 50%
Consolidated dry clay	1.65–2.25	Below 50%
Same, fissile	2.00–2.40	50%–60%
Same, lithified	2.25–2.65	Above 60%
Cherty phases	2.50–2.90	Above 95%

[56] See Dorsey, G. E., "The Present Status of the Carbon-ratio Theory," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 455–465, 1927, and Russell, W. L., "The Proofs of the Carbon-ratio Theory," *Ibid.*, Vol. 11, pp. 977–990, 1927.

[57] Wilson, J. H., "Lithological Character of Shale as an Index of Metamorphism," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 10, pp. 625–633, 1926.

OIL MIGRATION AND ACCUMULATION

Whether oil is produced in the beds in which it is found or enters them from some other source, it must nevertheless have migrated a greater or less distance, otherwise it should not be confined to the situations in which it is now found. It has unquestionably migrated, but its method of migration and the force impelling it to do so are not known, or at any rate are not agreed upon by students of oil geology.

Gravitation theory.—According to the unmodified anticline theory, oil, water and gas were supposed to distribute themselves solely as the result of the action of gravity; but this presupposes free movement of the three substances unimpeded by any opposing obstacles. Since, however, frictional and other resistances to moving liquids are known to exist in all rocks, many geologists are inclined to think that migration is due primarily to other causes than gravity, and that this latter force is active mainly in causing the fluids to arrange themselves in accordance with their specific gravities only after they have reached their permanent positions. The gravitational force which may actuate the relative movements of oil and water is so small that it is doubtful that it could accomplish any other result. Munn calculates that where the dip is 1 foot in 50 feet, the force available to separate oil from salt water and raise it up-dip is only about .0067 of the weight of the oil—a force too small to overcome the frictional resistance between oil and sand grains in capillary openings.

The gravitation theory implies that oil pools have been accumulating slowly, through a long period of time. If this be true but little pressure could develop in a pool before the oil would be forced out of any porous bed in which it might be accumulating into an overlying, even

though less porous, bed as rapidly as it was entering it. The fact that high pressure pools do exist in porous sandstones under shale beds of average porosity shows beyond doubt that the gravity theory fails to account for their presence.

HYDRAULIC THEORY.—According to Munn,[58] the oil and gas are concentrated into pools by moving water, which collects them and pushes them along.

The movement of the water, according to Munn, was accomplished by compression of the shale in which oil and water were originally present. When compression first began in the loose mud the interstitial water probably had ample room for movement between the particles of clay, without disturbing the oil which would adhere strongly to the clay surfaces. However, as the bed became more compact the particles of clay were more closely compressed and the oil films surrounding them were torn from their attachments and together with water formed an emulsion which filled the pores in the rock. With further compression both oil and water were forced from the shale into the sandstone above or below it or into any other contiguous rock with pores larger than those of the shale.

This is in brief the hydraulic theory. The oil and gas are held in the rock by an overlying mantle of water under hydraulic and capillary pressure, and not by impervious strata. Anticlines are favorable sites for the deposition of the oil because they serve to direct the water currents. Wherever the water currents form eddies, the oil will stop. If conflicting currents are absent there will be a tendency for the oil and gas to enter the more porous rocks where capillarity is too weak for the water to follow. "If portions of the sandstone should happen to be fine-grained

[58] Munn, M. J., "Studies in the Application of the Anticlinal Theory of Oil and Gas Accumulation," *Econ. Geol.*, Vol. 4, pp. 141–157 and 509–529, 1909.

while other portions were conglomeratic or unusually porous, the tendency of capillary movement would be to force the oil from the denser into the more porous portions," which would thereby become "pay streaks." Some pools might be formed by capillarity alone, others by hydraulic pressure and others by a combination of hydraulic and capillary movements.[59]

More than a decade later, Rich[60] reviewed the evidence that had accumulated since the publication of Munn's paper and asserted that the principal cause of the migration of oil and gas is the flushing action of moving underground water, and their accumulation is due to the fact that their buoyancy causes them to rise toward the surface of the moving water, where they are in a most favorable situation to be caught by anticlinal or other suitable traps as they are carried along in the current.

Capillary theory.—Washburne,[61] however, calls attention to the fact that capillarity varies directly as the surface tension of a fluid and inversely as the diameter of the pore. Water, having a greater surface tension than oil, will be more strongly affected by capillarity and will be drawn into the finest openings, displacing the oil. The oil and gas will, therefore, become concentrated into the coarsest spaces. Surface tension will then collect the dispersed oil into large masses which become the pools. If the circulatory movement of the water brings oil to the water-gas surface it is held there by surface tension and the film may increase by accretion. This is the capillary theory.

[59] Cf. also, Daly, M. R., "The Diastrophic Theory: A Contribution to the Study of the Mechanics of Oil and Gas Accumulation in Commercial Deposits," Am. Inst. Min. Engrs., *Bull.* 115, pp. 1137–1157, 1916.

[60] Rich, J. L., "Moving Underground Water as a Primary Cause of the Migration and Accumulation of Oil and Gas," *Econ. Geol.*, Vol. 16, pp. 347–371, 1921.

[61] Washburne, C. W., "The Capillary Concentration of Gas and Oil," Am. Inst. Min. Engrs., *Trans.*, Vol. 50, pp. 829–842, 1914.

OTHER THEORIES.—Other explanations of the causes of migration are: compacting of sediments, increasing temperatures at great depths, the generation of gases, and diastrophic movements. All of these are based on the postulate that the oil has been forced into the rocks in which it now occurs, whereas the capillary and hydraulic theories are applicable if the oil was formed in some of the members of the oil-bearing beds.[62]

At the present time the general tendency among oil geologists is to ascribe the movement of oil and gas through rocks largely to capillarity, but the mechanics of the process is not understood.

EXPERIMENTS ON THE MOVEMENTS OF OIL AND WATER IN ROCKS.—Among the most important experiments that have been undertaken to gain some idea as to the action of oil and water emulsions in adjacent beds of rocks with different porosities are those of Mills,[63] who as the result of his work concludes that "under ordinary field conditions the up-dip migration of oil and gas under the propulsive force of their buoyancy in water, as well as the migration of oil, either up- or down-dip, caused by hydraulic currents, are among the primary factors influencing both the accumulation and the recovery of oil and gas."

McCoy [64] ascribes the migration and accumulation of oil in water-saturated strata mainly to capillary forces and believes that oil does not migrate up-dip in consequence of differences in specific gravity between oil and water, and that it is not propelled through sands by hydraulic currents, but Mills refuses to accept these conclusions as generalizations, though he thinks they may be correct

[62] Ziegler, V., "The Movement of Oil and Gas Through Rocks," *Econ. Geol.*, Vol. 13, pp. 335–348, 1918.

[63] Mills, R. Van A., "Experimental Studies of Sub-surface Relations in Oil and Gas Fields," *Econ. Geol.*, Vol. 15, pp. 398–421, 1920.

[64] McCoy, A. W., "Notes on Principles of Oil Accumulation," *Jour. of Geol.*, Vol. 27, pp. 252–262, 1919, and a brief outline of some oil-accumulation problems: Am. Assoc. Petrol. Geol., *Bull.*, Vol. 10, pp. 1015–1034, 1926.

under exceptional conditions in small scale laboratory experiments.[65]

In a second series of experiments Mills[66] finds that the movements of water or of oil through sands is determined by the relation of the fluids to the sand before movement begins.

"When a water-saturated sand of irregular texture is invaded by oil, and conversely, when an oil-saturated sand of irregular texture is invaded by water, the fluid originally contained is retained most persistently in those parts of the bed that are of relatively fine, close texture.

"A water-saturated sand of fine texture is more permeable to water than to oil, and conversely, an oil-saturated sand of fine texture is more permeable to oil than to water.

"As an oil-saturated sand of fine texture becomes wet or saturated with water, it becomes increasingly permeable to water and decreasingly permeable to oil. Conversely, as a water-saturated sand of fine texture becomes wet or saturated with oil, it becomes increasingly permeable to oil and decreasingly permeable to water."

In other words generalizations as to the causes of the differential movements of oil and water into reservoir rocks and their movements to and fro in oil-bearing layers are not possible at present because dependent upon variable conditions the character of many of which is as yet unknown.

Recent experimental work has dealt with the details of the mechanics of the movements, and these, like the experiments of Mills, have shown that while capillarity is

[65] See discussion by McCoy and Mills in *Econ. Geol.*, Vol. 15, pp. 680–682, 1920, and Vol. 16, pp. 52–60, 1921.

[66] Mills, R. Van A., "Relations of Texture and Bedding to the Movements of Oil and Water Through Sands," *Econ. Geol.*, Vol. 16, pp. 124–141, 1921.

important in causing movements, the directions of the movements are determined by many complex conditions.

Dodd[67] has attempted to find the impelling cause of the movement of oil up low-angle dips and has reached the conclusion that neither buoyancy alone, nor difference in capillarity between oil and water, nor gas pressure alone will move oil any considerable distance under normal conditions; but the pressure of moving water will cause the migration of oil up or down any dip, provided the pressure is sufficient to distort the oil globules to the dimensions of the openings between pore spaces, and the migration is much more active when gas bubbles are present, provided the water conditions are not static.

Skirvin[68] has supplemented Mills' experiments and has found that water will remove oil from the coarser portions of an oil-saturated sand and that oil will replace water from the coarser portions of a water-saturated sand. Consequently, whether oil occurs in coarser or finer portions of a sand depends upon whether oil has replaced water or water has replaced oil. In other words, the invading liquid occupies the larger pores. Since commercial deposits of oil are usually found in the more open portions of a water-wet sand, the inference is clear that the oil has replaced water, and that the rôle of differential capillarity in the distribution of oil and water as related to their porosity is reduced in importance.

Further, Cook[69] has shown that water will creep along the walls of a narrow tube and enter an enlargement in the tube, displacing oil, which will flow in a direction opposite

[67] Dodd, H. V., "Some Preliminary Experiments on the Migration of Oil Up Low-angle Dips," *Econ. Geol.*, Vol. 17, pp. 274–291, 1922.

[68] Skirvin, O. W., "Experimental Study of the Invasion of Oil into a Water-wet Sand," *Econ. Geol.*, Vol. 17, pp. 461–469, 1922.

[69] Cook, C. W., "Capillary Relationships of Oil and Water," *Econ. Geol.*, Vol. 18, pp. 167–172, 1923, and discussion by C. W. Washburne, *Econ. Geol.*, Vol. 18, pp. 598–599, 1923.

to that from which the water has spread. Thus he shows that another force in addition to capillarity is active in producing oil migration. This he calls adhesion. It apparently is one of the most effective agents in causing the interchange of oil and water. Russell,[70] on the other hand, accumulated evidence to show that oil, under some conditions, was driven from the shales or limestones in which it originated into the sandstones which serve as reservoirs in masses large enough to be affected by buoyancy, and that these masses threaded their way towards the tops of anticlines by differences in head between the oil and water due to their differences in specific gravity. Russell also denies the possibility of the existence of water currents in oil sands.

The result of all the experimentation on the subject of oil migration leaves us with but an indefinite idea as to the causes that produce it. It has been shown that migration must occur, but whether the cause that actuates it is capillarity, adhesion, buoyancy or water currents has not yet been established. It is probable that all these factors are agencies and that they often act in conjunction to form large commercial pools. It is possible that some of them initiate the movement of the oil and others complete its accumulation in traps.

Effects of migration.—It has been thought by some geologists that the variation in the quality of the oil in different pools may be due to the distance it has migrated and the nature of the materials through which migration has taken place. It has been shown by experiments that a crude oil raised by capillarity through a column of fuller's earth will differentiate in such a way that the oil in the upper portion of the column will be lighter and will contain less sulphur than that left in its lower portion.

[70] Russell, W. L., "Some Experiments on Capillarity and Oil Migration," *Econ. Geol.*, Vol. 19, pp. 35–61, 1924.

This may explain in part the greater frequency of sweet oils in sandstone than in limestone.[71] Cook,[72] as the result of recent experiments, goes further and concludes: "(1) That alteration of petroleum may occur during capillary migration, either by fractionation or decomposition, and (2) that these actions may occur at relatively low temperatures and pressures."

OIL AND GAS WELLS

Oil and gas wells are openings drilled[73] into a pool through which sufficient oil or gas may be delivered at the surface to pay for the expense of securing it. Gas wells, of course, deliver their product at the surface without help. Oil wells may at first, because of the "rock pressure," deliver at the surface, but as the rock pressure recedes the oil is raised with less and less force until it ceases to flow, when pumping must be resorted to. Finally, so little oil is delivered at the bottom of the well that it will not pay for the cost of pumping and the well is abandoned.

The life of a well varies so widely that no estimate can be made of the period during which it may be profitable. The average life of the slow-yielding Pennsylvania wells is said to be seven years, but many last much longer before they are finally abandoned. A well dies as the result of the exhaustion of oil, in consequence of the influx

[71] Day, D. T., "Experiments on the Diffusion of Crude Petroleum Through Fuller's Earth," *Science*, New Ser., Vol. 17, pp. 1007–8, 1903; and Gilpin, J. E., and Bransky, O. A., "The Diffusion of Crude Petroleum Through Fuller's Earth, with Notes on Its Geological Significance," U. S. Geol. Sur., *Bull.* 475, 1911.

[72] Cook, C. W., "Fractionation of Petroleum During Capillary Migration," *Econ. Geol.*, Vol. XX, pp. 639–641, 1926, and "Fractionation and Decomposition of Petroleum During Capillary Migration," *ibid.*, Vol. XXII, pp. 230–232, 1927.

[73] Edson, F. A., "Diamond Drilling, with Special Reference to Oilfield Prospecting and Development," U. S. Bur. of Mines, *Bull.* 243, 1926.

of salt water or because of the clogging of the pores in the rock around the well.

The preservation of a well so that it may have a longer life, or the increasing of its yield after it has begun to fail are problems for the engineer rather than the geologist. The prolongation of the life of a well in a new field may be accomplished by controlling the gas [74] and using it to force the oil from its reservoir. In an old field when the rock pressure has fallen, due to the escape of the gas, the commonest means employed to increase the yield of the sand are flooding it, or subjecting it to the action of compressed gas or air through certain wells. A recently proposed method suggests that the oil sands be flooded with alkaline solutions to reduce the force with which the oil is held by the sand grains with which it is in contact.[75]

On the other hand, it is often necessary to reduce the flow of a well in which there is much gas, or to prevent its escape in small quantities from wells that are abandoned. This too is an engineering problem, the solution of which has been attempted in many ways.[76]

The average yield of wells is much smaller than is supposed by those who have not investigated the subject. In the United States at the present time it varies between one-third of a barrel to several hundred barrels daily in the different fields, in spite of the fact that some wells are "gushers" that produce enormous yields for short periods.

At Droojba, Russia, one well began production with a

[74] Miller, H. C., "Function of Natural Gas in the Production of Oil," Am. Petrol. Inst., N. Y.. 1929.

[75] Nutting, P. G., "Principles Underlying Soda Process," *Oil and Gas Jour.*, March 31 and May 5, 1927, and

Beckstrom, R. C. and Van Tuyl, F. M., "The Effect of Flooding Oil Sands With Alkaline Solutions," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 223–235, 1927.

For a summary discussion of methods for increasing the yield of wells see *Oil and Gas Jour.*, Dec. 1, 1927, p. 175.

[76] Lewis, J. W. and McMurray, W. F., "The Use of Mud-laden Fluid in Oil and Gas Wells," U. S. Bureau of Mines, *Bull.* 134, 1916.

flow of 50,000 barrels daily, which was thrown to a height of 300 feet. Another at Markoff, delivered 100,000 barrels daily at 400 feet. The Lucas well, Beaumont, Texas, for a time produced 75,000 barrels daily, and the Dos Bocas well in Mexico 250,000 barrels. The Lakeview well in California had an initial flow of 60,000 barrels for a few days and the Cerro Azul No. 4 in Mexico flowed 260,858 barrels in the first 24 hours. The oil from this well was shot 598 feet into the air, carrying with it two tons of drilling tools which it dropped 120 feet from the well.

The total yields of wells vary as greatly as their initial yields, being dependent upon so many factors that it is impossible to discuss them here. Naturally, the most important factor is the amount of oil and gas in the rock tributary to the well, and this in turn is dependent largely upon the thickness of the "sand," upon its porosity and upon the number of exits from it. It is conservatively estimated that some of the great gushers must drain 24 acres of sand 100 feet thick. In Oklahoma and Kansas where the average thickness of the sand is 20 feet and the delivery is about 10%, each well must drain about 3 acres. A common practice in some fields is to place 16 wells on a quarter section of land, on the assumption that 10 acres of oil-bearing rock will be thoroughly drained by each opening. Thompson[77] has estimated that up to 1925 the yield per acre of worked oil-fields in the United States had been approximately as follows:—

	Barrels Per Acre
Oil-fields of Paleozoic Age	1,200
Oil-fields of Mesozoic Age	4,600
Oil-fields of Tertiary Age	30,000

[77] Thompson, A. Beeby, "The Significance of Surface Oil Indications," Inst. Petr. Tech. (London), *Jour.*, Vol. 12, p. 620, 1926.

Under exceptional conditions the yield per acre is very large, and this is true particularly in fields characterized by salt domes. The cap-rock field at Spindletop, for instance, has yielded 190,000 barrels per acre, and the wells in the sands flanking the Spindletop dome have produced 850,000 barrels per acre in two years.

Naturally, if holes are driven into the producing sand within the drainage area of an existing well, the yield of this will be diminished. Consequently it is important as a matter of conservation of expense to so space the wells in any district that they will not drain each other's territory. The crowding of the wells at Beaumont and in some of the fields in California was an economic waste. Usually, however, in most fields, a well that strikes oil produces enough to pay expenses because of the great quantity of the material within circumscribed areas. In those districts in which drilling is very deep a well with an initial production of less than 200 barrels daily is considered a loss, unless the oil is of exceptionally high grade.

The number of oil wells in the United States and their average yield during 1926 is shown in the table on p. 115.

The number of wells annually drilled in the United States is about 28,000. In 1926 the number of wells drilled was 24,143, of which 60% were oil wells, 2,491 or 10% produced gas, and 7,210 or 30% were dry holes, and the daily average production of all oil wells was 6.8 barrels. In the ten-year period ending with 1927, the number of wells drilled east of California was 174,316 of which 25.9% were dry, 9.0% delivered only gas, 39.9% produced not more than 50 barrels of oil daily, 7.9% between 51 and 100 barrels daily and only 17.3% had an initial daily production of 100 barrels or more.[78] The total number of wells drilled between 1859 and the

[78] McIntyre, Jas., *Oil and Gas Jour.*, p. 184, Dec. 1, 1927.

TABLE XVII.—UNITED STATES PRODUCING OIL WELLS (1926)

State	*Number of Producing Wells*	*Daily Production (Barrels)*
Pennsylvania	76,800	0.3
Oklahoma	61,600	8.1
Ohio	39,250	0.5
Texas	29,030	17.4
West Virginia	20,150	0.8
Kansas	19,230	6.0
Illinois	16,270	1.3
New York	16,150	0.3
Kentucky	13,300	1.3
California	11,330	55.0
Louisiana	4,190	16.0
Indiana	2,050	1.1
Wyoming	3,400	21.8
Arkansas	4,500	37.2
Montana	830	29.8
Colorado	130	72.2
New Mexico	230	24.7
Michigan	90	5.3
Others	70	....
TOTAL IN UNITED STATES	318,600	6.8

end of 1927 was 740,764, of which 151,784 were dry. Of those that struck oil or gas about 55% are still producing.

GEOLOGICAL AGE OF OIL-BEARING FORMATIONS

Although oil is found within the United States at many horizons above the Cambrian, Thompson[79] concludes that on the whole the oil measures of Tertiary age are the most productive. They give the largest yield per acre (see p. 113), because they "are generally characterized by a much larger number of separate oil-bearing sands and a much greater thickness than those occurring in older rocks. In many Paleozoic and Mesozoic oil measures,

[79] Thompson, J. Beeby, "The Significance of Surface Oil Indications," Inst. Petr. Tech. (London), *Jour.*, Vol. 12, p. 620, 1926.

oil is restricted to one or several well-known sands or limestones separated by great thicknesses of barren beds, whilst in the majority of Tertiary measures oil may be found in almost any sandy lenticle in a succession that may reach thousands of feet in thickness." Oil and gas occur also in Pleistocene deposits. In glacial beds both have been found at shallow depths in sand lenses surrounded by clays or other impermeable or difficultly permeable materials.

The stratigraphic distribution [80] of the present production of petroleum throughout the world is shown in Fig. 40, and Fohs's estimate of the quantity of oil that has come from the rocks of the several geological eras is given in Table XVIII. [81]

TABLE XVIII.—STRATIGRAPHIC PRODUCTION OF PETROLEUM
Compiled by F. Julius Fohs

Oil Province or Country	*Production to January 1st, 1927. (Barrels.)*		
	Paleozoic	*Mesozoic*	*Tertiary*
Appalachian	2,265,228,000		
E. Mississippi Valley (Est.)	593,500,000		
Kansas	426,106,000		
Oklahoma	1,983,159,000		
Texas Panhandle	25,424,000		
N. Central Texas (Part estimated)	506,314,000		
W. Texas	26,951,000		
Gulf Cretaceous—E. Texas (Part estimated)		252,100,000	
Gulf Cretaceous—Arkansas and Louisiana		539,716,000	
Gulf Coast			579,349,000

[80] Fohs, F. J., "Stratigraphic Distribution of Petroleum," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 11, p. 764, 1927.

[81] The figure is a reproduction of Mr. Fohs's original figure, with the exception of certain corrections made by its author. The data for the table were furnished by Mr. Fohs, with permission to print.

Oil Province or Country	*Production to January 1st, 1927. (Barrels.)*		
	Paleozoic	*Mesozoic*	*Tertiary*
Rocky Mountain		293,878,000	
California			2,509,665,000
Canada	25,832,000		
Mexico		1,407,003,000	
Venezuela			73,710,000
Trinidad			33,454,000
Colombia			8,710,000
Ecuador (Estimated)			1,150,000
Peru			72,998,000
Argentine			32,523,000
France—Alsace			3,879,000
Germany—Hanover		17,758,000	
Italy			1,276,000
Galicia—Poland & Czecho-slovakia			202,246,000
Roumania			247,971,000
Russia			2,164,064,000
Persia			217,392,000
Egypt			14,217,000
Algeria			95,000
India			171,620,000
Japan and Formosa			55,709,000
East Indies			357,145,000
TOTALS	5,852,514,000	2,510,455,000	6,747,173,000
TOTAL WORLD PRODUCTION			15,110,142,000

The braces signify that some production comes from rocks of other eras than that heading the column in which the figures are placed.

STRATIGRAPHIC DISTRIBUTION OF PETROLEUM

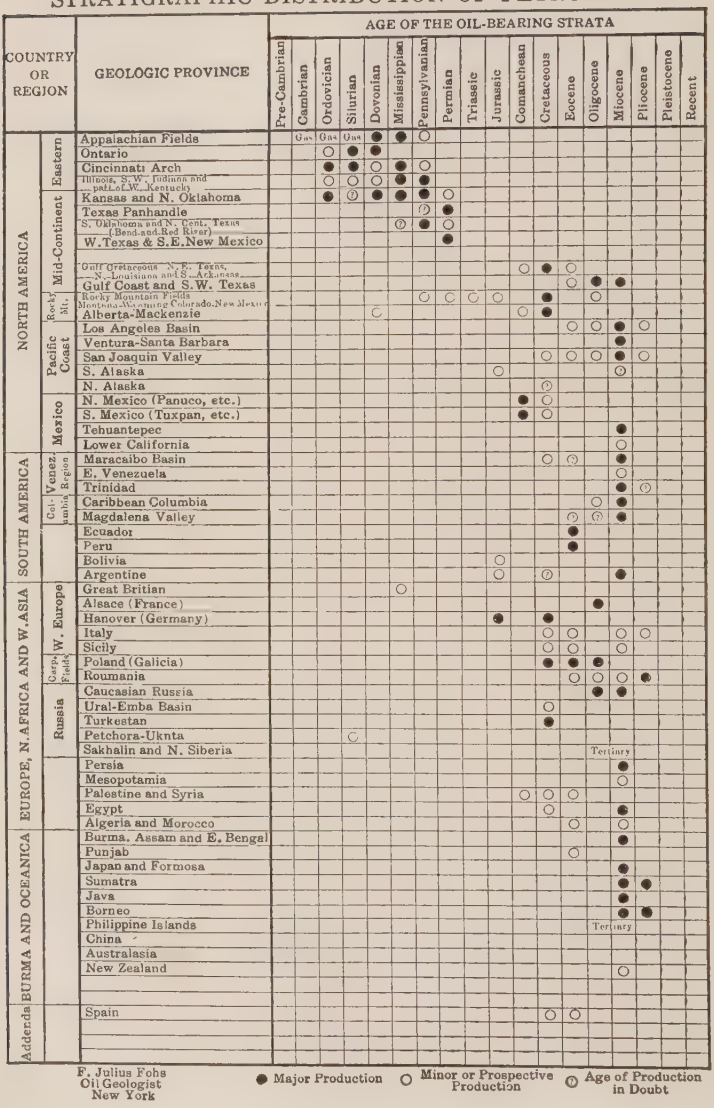


FIG. 40.—Table showing stratigraphic distribution of petroleum. (*Courtesy of F. J. Fohs.*)

PRODUCING FIELDS IN THE UNITED STATES [82]

APPALACHIAN FIELD.—The Appalachian field [83] was the first one to be developed in the United States. It lies west of the Appalachian Mountains in Pennsylvania, New York, and West Virginia, and in Eastern Ohio, Kentucky, and Tennessee, in a great synclinal basin of Paleozoic

FIG. 41.—Sketch map showing approximate positions of producing oil fields in the United States.

1. Appalachian.
2. Lima-Indiana.
3. Michigan.
4. Illinois.
5. Mid-Continent.
6. Gulf Coast.
7. Rocky Mountain.
8. California.

rocks in which are many minor folds that determine the positions of the known oil and gas pools (Fig. 42).

The oil is produced from sandstones of Devonian, Mississippian and Pennsylvanian ages in New York, Pennsylvania, and West Virginia, mainly from the "Clinton" (Silurian) sandy shale in Eastern Ohio, mainly from the

[82] Excellent descriptions of typical pools in many of these fields are found in the publication of the Am. Assoc. of Petrol. Geologists already referred to, viz.: *Structure of Typical American Oil Fields*. A symposium. Vols. I and II, Tulsa. Okla., 1929.

[83] M. L. Fuller, "Appalachian Oil Fields," Geol. Soc. Amer. *Bull.*, Vol. 28, pp. 617–654, 1917.

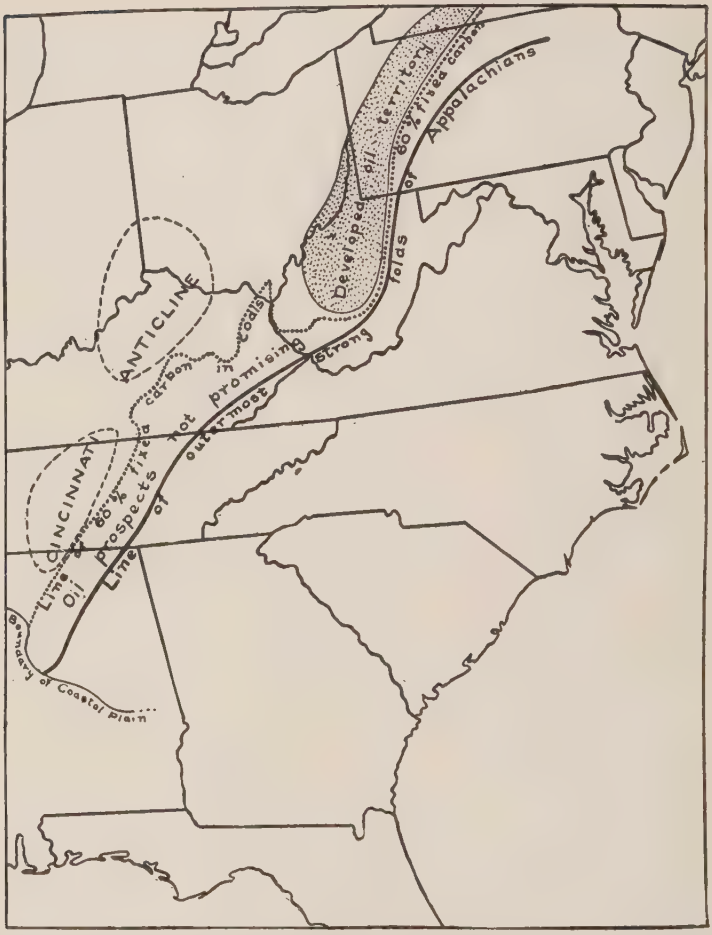


FIG. 42.—Sketch map of Appalachian region, showing relation of developed oil field to the 60% isovol. With a few minor exceptions, neither oil nor gas has been found east of the western face of the outer-most strong fold of the Appalachians. Between this face and the 60% fixed carbon line there is some gas in the north and a smaller amount in the south, and an occasional small oil pool. The absence of oil west and south of the developed field as mapped is due to unfavorable stratigraphic and structural conditions. (*After Fuller, Bull. Geol. Soc. Amer., 1916.*)

Berea sandstone (Mississippian) in Eastern Kentucky, and mainly from the Ordovician and Mississippian limestones in Tennessee. The oil is practically free from sulphur, has a paraffin base and is of the highest grade. This district contains enormous quantities of coal in addition to the oil. Towards the southeast near the Appalachians the carbon-ratios (p. 97) exceed 60% and oil production ceases. Gas is found in all of the oil-bearing formations and also in some Cambrian beds. Much gas is also produced from the area lying between the 60% and 65% isovols, with minor quantities up to the 70% isovol.

Lima-Indiana field.—The Lima-Indiana field[84] in northwestern Ohio and northeastern Indiana comprises a narrow belt extending from Marion, Indiana, northeastward to Lake Erie, with an extension into southwest Ontario.[85] The district is a broad flat-topped arch on the northwest side of the larger Cincinnati anticline. The oil is in Trenton (Ordovician) limestone and is sour. It is accompanied by much gas.

Michigan field.—The older Michigan field[86] lies on the southeast side of the basin which makes up most of the southern peninsula. Here there are a few pools in minor folds on the eastern limb of the syncline and the field extends into Ontario where it overlaps Onondaga and other Devonian limestones.

Farther north, in the Saginaw and Muskegon districts new fields have been found. Production is from the Berea (Mississippian) sandstone and also from Devonian limestones.

[84] Bownocker, J. A., "Petroleum in Ohio and Indiana," Geol. Soc. Amer. *Bull.*, Vol. 28, pp. 667–676, 1917.

[85] Miller, W. G., "Petroleum in Canada," Geol. Soc. Amer. *Bull.*, Vol. 28, pp. 221–226, 1917.

[86] Smith, R. A., "The Occurrence of Oil and Gas in Michigan," Mich. Geol. and Biol. Sur., *Pub.* 14, *Geol. Ser.* 11, pp. 1–281, 1914.

Illinois field.—The Illinois field is in a comparatively narrow belt extending a little west of north from the southwest corner of Indiana for 80 or 90 miles into Illinois.[87] The principal pools are in sands near the crest of the La Salle anticline. Other less important pools are in the western part of the State on domes on the eastern flank of the Illinois basin of Paleozoic rocks. Both heavy and light paraffin and asphalt oils occur, often in the same sands and gas accompanies both types.

In Illinois and southwestern Indiana most of the oil comes from the Mississippian and Pennsylvanian beds, though minor quantities are produced from sands in the Devonian, Silurian and the upper portion of the Ordovician.

The principal Kentucky[88] fields form a southern extension of the Illinois fields and produce almost exclusively from Onondaga (Devonian) limestone.

Mid-Continent fields.—The Mid-Continent[89] fields include the oil-producing areas in Oklahoma, Kansas, Missouri, Arkansas, and those in northern and central Texas and northern Louisiana. The oil, which is of mixed base, occurs in domes, anticlines, terraces, lenses and corrugated monoclines. Gas is abundant. Petroleum is found in almost every formation from the Ordovician to the Tertiary with the exception of the Triassic and Jurassic. During the past few years deeper drilling has been carried on in most of the fields with the result that enormous production has been obtained from Lower Paleozoic formations which were formerly considered non-productive.

[87] Kay, F. H., "Oil Fields of Illinois," Geol. Soc. Amer. *Bull.*, Vol. 28, pp. 655–666, 1917.

[88] Jillson, W. A., "Geological Factors in the Recovery of Oil and Gas in Kentucky," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 4, pp. 303–312, 1920.

[89] Gardner, J. H., "The Mid-Continent Oil Fields," Geol. Soc. Amer. *Bull.*, Vol. 28, pp. 685–720, 1917.

Kansas[90] and Oklahoma[91] obtain much of their present production from the Wilcox sand of probable Upper Ordovician age, as well as from the Arbuckle and Siliceous (Ordovician) lime. A small amount has been produced from the Hunton lime (Devonian) in a few scattered fields.

The earlier production in Oklahoma and Kansas, as well as that of north central Texas,[92] was from sandstones and limestones of Pennsylvanian and Mississippian age.

In West Texas and the Panhandle, oil is found in limestones, that are probably Permian, which underlie a great thickness of salt and anhydrite. In the Panhandle district the reservoir rocks lie on the flanks of a granite ridge which probably formed an island in the Permian sea, and immediately overlying the granite is a porous arkose, locally known as "granite wash" which is also highly petroliferous. This district contains one of the largest known gas fields.[93]

In the Permian basin of West Texas, oil fields, including some of the most prolific fields found in the United States, have been found on limestone "highs" in the central part of the basin. The reservoir rocks are Permian limestones.

The Bend Arch which extends north from the Llano-Burnet uplift forms the eastern border of the basin and on this a number of fields have been found in the Ranger-Wichita Falls district which produce large quantities

[90] Moore, R. C., "The Relation of the Buried Granite in Kansas to Oil Production," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 4, pp. 255–261, 1920.
Rich, J. L., "Shoestring Sands of Eastern Kansas," *Ibid.*, Vol. 7, pp. 103–113, 1923.

[91] Moore, R. C., "Relation of Mountain Folding to the Oil and Gas Fields of Southern Oklahoma," *Ibid.*, Vol. 5, pp. 32–48, 1922.

[92] Adams, H. H., "Geological Structure of Eastland and Stephens Counties, Texas," *Ibid.*, Vol. 4, pp. 150–167, 1920.
Hubbard, W. E., and Thompson, W. C., "The Geology and Oil Fields of Archer County, Texas," *Ibid.*, Vol. 10, pp. 457–482, 1926.

[93] Bauer, C. M., "Oil and Gas Fields of the Texas Panhandle," *Ibid.*, Vol. 10, pp. 733–746, 1926.

of oil from uppermost Mississippian and Lower Pennsylvanian limestones and from Upper Pennsylvanian sands.

Other fields have been found between the Bend Arch and the Basin to the west.

To the south and east of these fields is a fault zone, known as the Balcones-Mexia fault zone,[93a] which extends from the Mexican border to northeastern Texas, and along which oil is found at many places. Near San Antonio the oil occurs in the Edwards (Comanchean) limestone[94] and in volcanic rocks, generally referred to as "serpentine," overlying the Austin chalk[95] (Cretaceous). Towards the northeastern (Mexia) end of the zone production is mainly from the Cretaceous, although some oil has been found in the Comanchean.

To the east and northeast of the Mexia fault zone there are a number of important fields in Louisiana[96] and Arkansas[97] in which oil is found in sands of Cretaceous and early Tertiary age, and recent deep drilling has also proven it to exist in the Comanchean.

Gulf coast fields.—The Gulf coast fields border the Gulf of Mexico from northern Mexico to southwestern Louisiana. Here the oil, which is asphaltic, occurs in rocks of Cenozoic age closely associated with salt domes.

[93a] Lahee, F. H., "Oil and Gas Fields of the Mexia and Tehuacana Fault Zones, Texas," *Structure of Typical American Oil Fields*, Amer. Assoc. Petrol. Geol., Vol. 1, pp. 304–388, 1929.

[94] Sellards, E. H., "The Luling Oil Field in Caldwell County, Texas," *Ibid.*, Vol. 8, pp. 175–188, 1924.

[95] Collingwood, D. M., and Rettger, R. E., "The Lytton Springs Oil Field, Caldwell County, Texas," *Ibid.*, Vol. 10, pp. 953–975, 1926.

[96] Hull, P. D., and Spooner, W. C., "A Review of Oil and Gas Pools in Northern Louisiana," *Ibid.*, Vol. 6, pp. 179–192, 1922.

Powers, Sidney, "The Sabine Uplift, Louisiana," *Ibid.*, Vol. 4, pp. 117–136, 1920.

[97] Schneider, H. G., "Smackover Oil Field, Ouachita and Union Counties, Arkansas," Amer. Inst. Min. & Met. Eng., *Trans.*, Vol. 70, pp. 1076–1099, 1924.

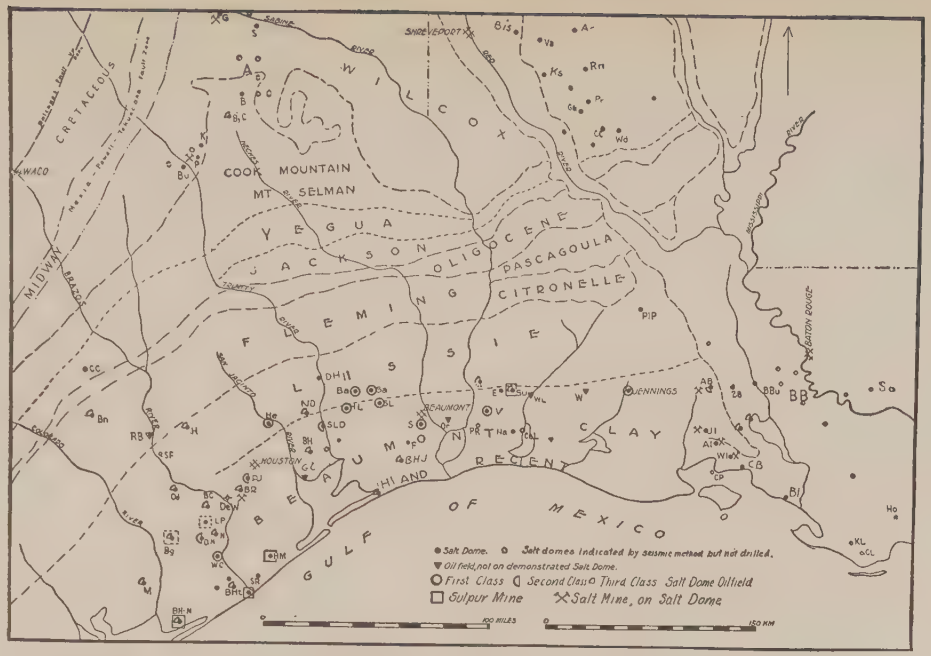


FIG. 43.—Map of the salt domes of Texas and Louisiana, showing the first, second and third class salt dome oil fields, the sulphur mines, and the salt mines on the salt domes. The three salt domes in South Texas, Palangana with a small sulphur deposit, Piedras Pintas with a small oil field, and Falfurrias with a gypsum deposit, are to the south of the area of this map, and are not shown on it. Oil has been discovered in commercial quantity on the DeWalt (DeW), Bayou Bouillion (BBu), and Sorrento (So) domes. (*After D. C. Barton, Univ. of Texas Bull. 2801.*)

Two zones are known, one along the coast and the other, the interior salt domes, inland (Fig. 43).

Rocky Mountain fields.—The Rocky Mountain fields embrace a large number of pools scattered rather irregularly through portions of Wyoming,[98] Montana,[99] and Colorado and a few in New Mexico[100] and Utah. The character of the oil varies from light to heavy and some wells produce only gas. The pools are on domes and anticlines. In these fields the principal oil horizons are in the Cretaceous, though other horizons are Mississippian, Permian, Triassic and Tertiary (mainly Eocene).

In New Mexico some of the oil is in Permian limestones on the flank of the West Texas salt basin and some is in sandstones chiefly of Cretaceous age. Production in Colorado is scattered, the best known pool being the Florence Pool where the oil is associated with shales of Cretaceous age. In Wyoming oil occurs in many formations. The highest grade oil comes from the Mesozoic (mainly Jurassic and Cretaceous) beds of Salt Creek and heavy oil from many places in the Embar (Permian) limestone. Montana's production comes mainly from Jurassic sands and Mississippian limestone.[100a]

California fields.—In the California district the oil fields are in two groups, of which one lies in the valleys between the ranges near the coast and on their slopes.[101]

[98] Heald, K. C., "Oil Bearing Horizons of Wyoming," Amer. Assoc. Petrol. Geol., Vol. 5, pp. 186–211. 1921.

Bartram, J. G., "Occurrence of Black Oil in Wyoming," *Ibid.*, Vol. 10, pp. 445–448, 1926.

[99] Heald, K. C., "The Kevin-Sunburst Oil Field, Montana," *Ibid.*, Vol. 10, p. 197, 1926.

[100] Knox, J. K., "Geology of New Mexico as an Index to Probable Oil Resources," *Ibid.*, Vol. 4, pp. 94–112, 1920.

[100a] Collier, A. J., "The Kevin-Sunburst Oil Field and other Possibilities of Oil and Gas in the Sweetgrass Arch, Montana," U. S. Geol. Sur., *Bull.* 812-B., pp. 57–189, 1929.

[101] Arnold, R., "New Oil Fields of the Los Angeles Basin, California," *Ibid.*, Vol. 6, pp. 303–316, 1922.

McLaughlin, R. P.,"California Oil Fields," *Ibid.*,Vol. 5, pp. 623–625, 1921.

The rocks are partly unconsolidated and in most fields are strongly deformed. The beds dip at high angles and many of them are sealed by plugs of asphalt and paraffin. The oils are of medium to heavy grade and are mainly asphaltic. They occur on minor folds in the major monoclines and in small folds and in faults on independent anticlines. The oil is found in all formations from the Upper Cretaceous to the Pleistocene, but the largest production is from the Miocene.

The other group, comprising the northern California fields (Fig. 44), is in the southern part of the San Joaquin Valley.[102] Its oil is similar to that of the southern group.

CLASSIFICATION OF OIL FIELDS WITH REFERENCE TO STRUCTURE

The classification of the oil fields of the United States as given above is geographical. Ver Wiebe[103] points out the fact that the distribution of the oil-bearing areas is determined by the structures in the rocks and that another classification, which might well supplement the geographical classification, can be based on the tectonic features of the country. He shows that the oil fields are grouped around the borders of great tectonic elements, either on the sides of great basins or adjacent to the axes of arches between the basins. The large areas whose positions are controlled by the major folds he calls provinces, those areas within the provinces that possess distinctive minor structures are called districts, smaller areas within districts he would call fields. The term "pool" he would limit to an uninterrupted accumulation of oil drained by a single well or a number of wells. The "field" in this sense would

[102] Stevens, P. A., "A Comparative Study of San Joaquin Valley Oil Fields," *Ibid.*, Vol. 8, pp. 29–40, 1924.

[103] Ver Wiebe, W. A., "Tectonic Classification of Oil Fields in the United States," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 13, pp. 109–140, 1929.

FIG. 44.—Airplane view of Midway oil field, Cal., showing distribution of wells. City of Taft at right. (*Courtesy of the Oil Age, Los Angeles.*)

include veral pools, which are separated from one another by barren territory.

Ver Wiebe's classification is shown in the table on pages 130 and 131, and the position of his provinces in the map (Fig. 45).

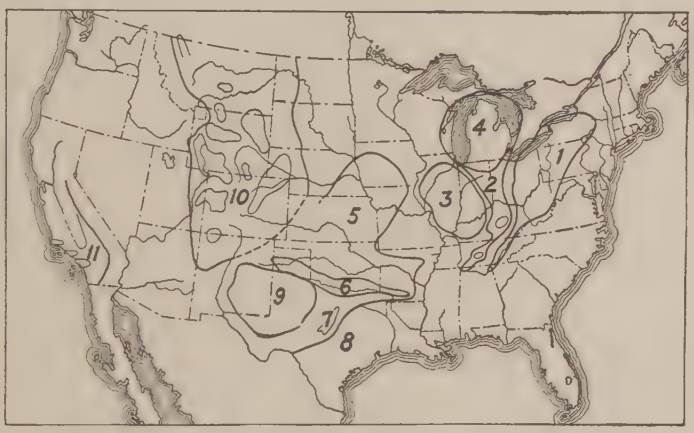


FIG. 45.—Petroliferous provinces in the United States:

1. Appalachian geosyncline.
2. Cincinnati arch.
3. Eastern Interior coal basin.
4. Michigan basin.
5. Western Interior coal basin.
6. Ouachita-Amarillo Mountain.
7. Bend arch.
8. Gulf embayment.
9. West Texas.
10. Rocky Mountain geosyncline.
11. Pacific geosyncline.

PRODUCTION IN THE UNITED STATES

OIL.—The production of petroleum in the United States naturally varies from year to year by amounts depending upon the relation between the exhaustion of old fields and the additions made by wells in newly discovered fields. In 1923 the production was about 732,400,000 barrels; in 1924 about 713,950,000 barrels; in 1925 about 763,750,000 barrels; and in 1927 about 901,129,000 barrels, with a value of $1,172,830,000 at the wells. The distribution and value of the production in 1928 are shown in the table on page 132.

TABLE XIX.—TABLE OF PETROLIFEROUS PROVINCES

Province	*District*	*Area Involved*
1. Appalachian Geosyncline		New York, Pennsylvania, West Virginia, Eastern Ohio, Eastern Kentucky
2. Cincinnati Arch	Lima-Indiana	Western Ohio, Eastern Indiana
	Cumberland Saddle	South-central Kentucky, North-central Tennessee
	Alabama-Mississippi	Alabama, Mississippi
3. Eastern Interior Coal Basin		Northwestern Kentucky, Illinois, Southwestern Indiana
4. Michigan Basin		Michigan
5. Western Interior Coal Basin		Kansas, Northern Oklahoma
6. Ouachita-Amarillo Mountain	Arbuckle-Wichita	Southern Oklahoma
	Red River	North-central Texas
	Amarillo Mountain	Texas Panhandle
7. Bend Arch		North-central Texas
8. Gulf Embayment	Balcones Fault	Eastern Texas
	Reynosa Escarpment	Southern Texas
	Sabine-Ouachita Uplifts	Northern Louisiana, Southern Arkansas
	Salt Dome	East Texas, Southern Texas, Southern Louisiana
9. West Texas		Western Texas, Southeastern New Mexico

Province	*District*	*Area Involved*
10. Rocky Mountain Geosyncline	Big Horn Basin	Wyoming, Montana
	Wind River Basin	Wyoming (central)
	Green River Basin	Southwestern Wyoming, Northwestern Colorado
	Laramie Basin	Southeastern Wyoming
	Powder River Basin	Northeastern Wyoming
	Sweetgrass Arch	Northern Montana
	Big Snowy Anticlinorium	Central Montana
	Eastern Colorado	Eastern Colorado
	Uinta Basin	Northwestern Colorado, Northeastern Utah
	San Juan Basin	NorthwesternNewMexico
		Utah
11. Pacific Geosyncline	San Joaquin Valley	California
	Santa Maria	California
	Ventura	California
	Los Angeles Basin	California

TABLE XX.—PETROLEUM PRODUCED IN THE UNITED STATES IN 1928 (BY FIELDS)

	Production (In Thousands of Barrels)	*Value at Wells*	
		Total (In Thousands of Dollars)	*Average per Barrel*
Appalachian	30,968	83,100	2.70
Lima-Indiana	1,677	2,600	1.55
Michigan	595	900	1.51
Illinois and Southwestern Indiana	7,422	11,300	1.51
Mid-Continent	552,980	645,300	1.17
Gulf Coast	45,719	55,300	1.21
Rocky Mountain	29,021	37,900	1.30
California	231,982	241,500	1.04
	900,364	1,077,900	1.20

The producing area of each field in 1923 and the average specific gravity of its oil was:

	Acres	*Average Specific Gravity*
Appalachian	2,000,000	.8203
Lima-Indiana	300,000	.8448
Illinois and Southwestern Indiana	160,000	.8628
Mid-Continent	1,600,000	.8498
Gulf Coast	25,000	.9188
Rocky Mountain	55,000	.8373
California	60,000	.8956
	4,200,000	.8654

The imports of crude oil during 1928 were 79,766,672 barrels, mainly from Mexico and Venezuela and the exports 18,961,362 barrels, mainly to Canada and Japan. In addition 11,680,254 barrels of gasoline and other

petroleum products were imported and 126,104,732 barrels exported.

In addition to the crude oil produced and imported in 1927 there were made in United States experimental plants in California, Wyoming and Colorado about 270,000

TABLE XXI.—SUMMARY OF STATISTICS FOR NATURAL GAS IN THE UNITED STATES, 1921–1926

	1921	1923	1926
Natural Gas Consumed:			
Domestic (millions of cubic feet)	248,334	277,050	289,175
Industrial (millions of cubic feet):			
Carbon black	50,565	109,096	130,321
Field	182,305	343,076	478,188
Other industrial	180,848	277,745	415,169
Treated for Natural-gas Gasoline:			
Millions of cubic feet	465,097	875,711	1,206,300
Per cent of total consumption	70.3	87.0	92.0
Natural-gas Gasoline (raw):			
Quantity (thousands of gallons)	449,934	816,226	1,363,090
Value at plants:			
Total (thousands of dollars)	61,815	77,268	136,412
Average per gallon (cents)	13.7	9.5	10.0
Carbon Black:			
Quantity (thousands of pounds)	59,766	138,263	180,576
Value at plants:			
Total (thousands of dollars)	5,446	11,692	9,939
Average per pound (cents)	9.1	8.5	5.5

gallons of shale-oil with an average specific gravity of 12° Bé., representing an average recovery of about 32 gallons per ton of shale treated, and, in 1928, 1,776,000,000 gallons of unblended gasoline, extracted from 1,500,000,000,000 cubic feet of natural gas,[194] or about 1.2 gallons per 1,000 cubic feet. In 1927 the quantity was 1,641,144,000 gallons or 39,075,000 barrels, extracted from 1,341,248,000,000 cubic feet of gas.

[194] Burrell, G. A. and others. "The Condensation of Gasoline from Natural Gas," U. S. Bureau of Mines, *Bull.* 88, 1915.

Gas.—The total commercial production of natural gas in the United States during 1928 was about 1,540,000 million cubic feet with an estimated value of about $333,000 at points of consumption. About 22% was used for domestic purposes, 10% in the manufacture of carbon black, 31.5% for other industrial purposes and 36.5% was consumed in the field. The rapid growth in the utilization of the gas is shown in Table XXI, as is also the rapid increase in the value of its by-products. About 92% of the gas produced is now treated for the recovery of gasoline of which the amount extracted in 1926 was about one tenth of all the motor fuel produced. The average yield per 1,000 cubic feet of gas treated was 1.1 gallons, and the number of extracting plants operating was 1,102 of which 297 were in Oklahoma.

RESERVES IN THE UNITED STATES

The enormous annual production of oil in the United States has led many economists and geologists to consider seriously the possibility of exhaustion of the oil measures and the consequent economic changes that will result.

Arnold[105] as long ago as 1915 uttered a warning that the end of the petroleum resources of the country was in sight and estimated that with an approximate annual consumption of 265,000,000 barrels (which was the rate in 1914), the supply would last about 22 years. He further[106] made a survey of the possible resources of the world and concluded that care should be taken to conserve the petroleum if it is desired to save it for the uses to which it is best adapted, and deplored particularly its use as fuel.

[105] Arnold, R., "The Petroleum Resources of the United States," *Econ. Geol.*, Vol. 10, pp. 695–712, 1915.

[106] Arnold, R., "Conservation of the Oil and Gas Resources of the Americas," *Econ. Geol.*, Vol. 11, pp. 203–222 and 299–326, 1916.

Veatch,[107] calls attention, however, to the fact that it is impossible to express exhaustion of petroleum reserves in terms of years. "Long before the world has reached a stage when high prices will fail to bring temporary over-production * * * petroleum prices will approach the economic limit, which will, on the one hand, curtail certain uses of petroleum products, and on the other will make it commercially feasible to manufacture substitutes for many petroleum products or to derive them more extensively by distillation from * * oil-shale deposits, or * * the high volatile coals."

That the oil supply is not unlimited is, however, appreciated by all geologists and recently a careful study has been made of the known and probable reserves in this country and its neighbors by White[108] and by a committee of geologists appointed by the American Petroleum Institute.[109] The Government has accepted the conclusions of the Committee in its endeavor to tax oil properties at a fair valuation, from year to year.

As a result of the study it has been found that the only basis upon which the amount of reserve oil can be estimated is the record of production in the past. Thousands of records of producing properties have been tabulated and studied and graphs have been drawn that show the rate of depletion of the different oil sands as production proceeds. From these data it is calculated that the future recovery of oil by the wells that are now producing, or under the present methods of treatment, will aggregate 5,321,427,000 barrels. In addition there will remain in the ground 26,000,000,000 barrels of oil, much of which may be recovered by new methods of treatment in the future.[110]

[107] Veatch, A. C., "Estimation of Petroleum Resources," *Econ. Geol.*, Vol. 17, pp. 132–139, 1922.

[108] White, D., "The Oil Supply of the World," *Oil News*, Vol. 11, p. 39, May 20, 1923.

[109] *American Petroleum Supply and Demand.* New York, 1925.

[110] See McIntyre, Jas., "Great Progress in the Recovery of Oil," *Oil and Gas Jour.*, Dec. 1, 1927, p. 175.

Moreover, casing head gasoline may be obtained from natural gas that is equivalent to the yield of 1,000,000,000 barrels of crude oil, and a large additional quantity of motor fuel may be produced by cracking shale-oil [111] and tars of several kinds.[112]

The total reserve of oil, therefore, in areas known to be productive, is 32,000,000,000 barrels. No allowance has been made for any oil in fields that may be discovered in the future, although it is quite certain that there are numerous small fields in the country, and probably some large ones that have not yet been explored, nor has any consideration been given to the probable large reserves in known fields at depths greater than those now reached by the drill. However, it is becoming more expensive to find new fields each year, so that the oil produced in the future will cost more than that produced in the past, and, consequently, the problem of oil production in the near future will be one of cost rather than one of the abundance of the commodity.[113]

The total area in which the discovery of new fields is possible is 1,105,455,000 acres. Anywhere throughout this acreage new fields may be discovered. Moreover, in the present producing areas it is certain that there are other

[111] McIntyre, Jas., "Extent of Oil Reserves Misunderstood," *Ibid.*, Dec. 1, 1927, p. 188.

[112] Morrell, J. C., and Egloff, G., "Many Future Sources of Motor Fuel," *Ibid.*, Sept. 22, 1927, pp. 202, 400, 420 and 424.

[113] The cost of finding new oil fields of certain types has recently been greatly diminished by the use of geophysical methods. For an outline of the principles underlying these methods see: A. M. Rowley, "Science Employed in Search for Oil," *Oil and Gas Jour.*, Dec. 1, 1927, pp. 172 and 208, and D. C. Barton, "Applied Geophysical Methods in America," *Econ. Geol.*, Vol. 22, pp. 649–668, 1927.

A thorough discussion of the theories underlying the different geophysical methods employed in prospecting for oil and ores, and descriptions of their practical applications will be found in *Elements of Geophysics, as Applied to Explorations for Minerals, Oil and Gas*, by R. Ambronn. Trans. by M. C. Cobb. New York, 1928 and *Geophysical Prospecting*. A. I. M. & M. Eng., New York, 1929.

horizons than those now producing from which oil may be obtained. Most of these horizons are beneath those now producing, and if the increase in the carbon-ratio is not to be regarded as indicating unfavorable conditions, it is probable that many of them may become productive when penetrated by deep borings.[114]

Moreover, the application of geophysical methods of exploration has recently revealed the presence of many hitherto unsuspected salt domes in Texas and neighboring States, some of which may be the sites of important oil accumulations (compare pp. 74–77). Barton [115] infers that the reserve in producing salt domes in the two States named may be as great as 520,000,000 barrels and those in undeveloped salt domes at about 3,000,000,000 barrels.

FOREIGN PRODUCING FIELDS

The principal producing countries outside of the United States are Venezuela, Russia, Mexico, Persia, the Dutch East Indies and Rumania. Colombia, Argentina and Peru are rapidly entering the ranks of important producers, but their annual yield in 1927 was still less than 2½% of the total yield of all countries (Fig. 46).

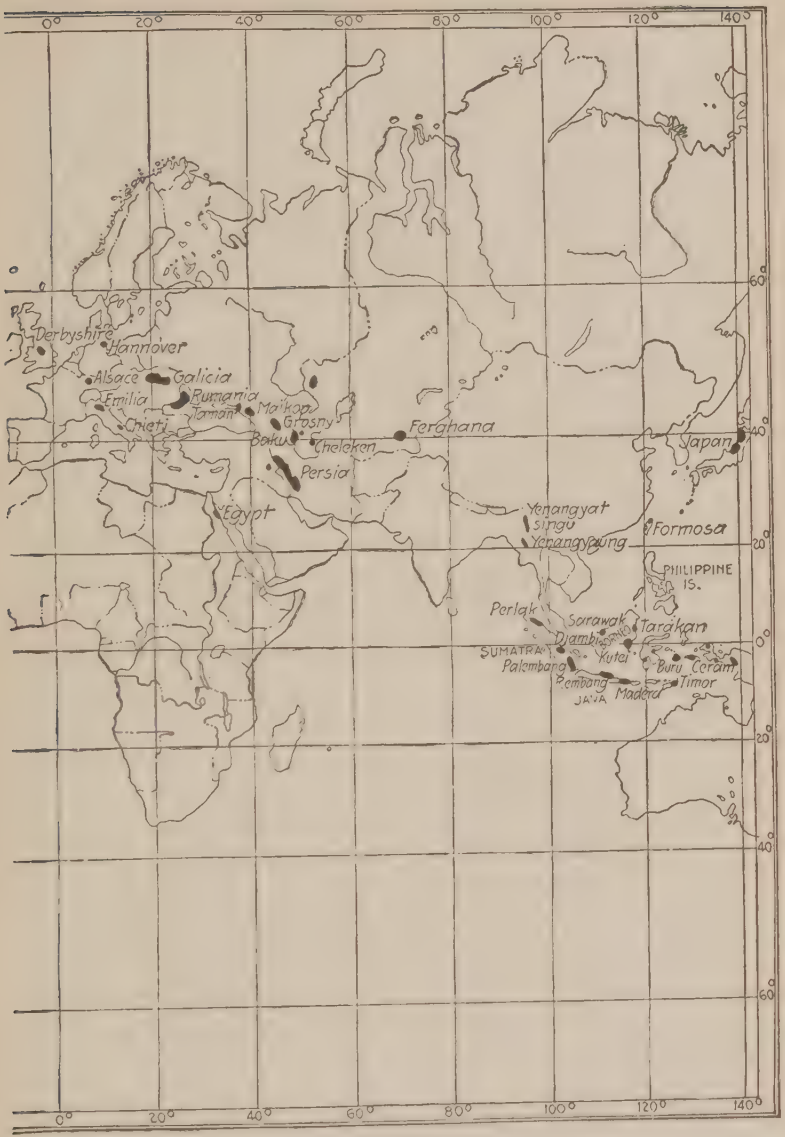
North America.—North America produces by far the major portion of the petroleum of the world.

Mexico.—The rapid increase in the production of Mexico, from 3,600,000 barrels in 1910 to 185,000,000 barrels in 1922, gave promise that this country would outstrip the United States as the principal producer of oil in the world. But in 1922 many of the largest wells were ruined by an influx of salt water and since that time the

[114] In the *Oil and Gas Jour.*, Vol. 26, No. 28, Dec. 1, 1927, pp. 116–207, is an interesting summary of the status of the oil industry at that time, including discussions of reserves, of production methods, of refining methods, costs of drilling, etc.

[115] Barton, D. C., "The Economic Importance of Salt Domes," University of Texas, *Bull.* 2801, 1928.

FIG. 46.—Map of principal oil-producing fields in the



World. (*After Emmons, General Economic Geology.*)

invasion has so steadily continued that new discoveries have not been able to make up the loss from the wells that had to be abandoned, and as a result the future of Mexico is not regarded as very promising. Mexican oil stocks have fallen in value and only very strong companies now find it possible to finance new explorations. It is thought by Mexican producers, on the other hand, that carefully planned and conducted development of the unexploited regions and more careful handling of the new wells that may be brought in will at least keep the nation in the forefront of producing countries, even if its production is not notably increased. The principal oil districts in Mexico [116] are (Fig. 47):

Panuco, 25 miles southwest of Tampico on the Gulf of Mexico. In this district are the Panuco, Topila and Ebana fields, all of which yield an asphaltic oil from Tertiary and Cretaceous rocks. It is used mainly for fuel.

Dos Bocas-Alamo, "The Golden Lane," or "Knife Edge," a narrow belt less than one mile wide and about 40 miles long situated west and northwest of Tuxpam. At present the district is flooded, but formerly it was the greatest producing area of equal size in the world, since for several years each of three wells produced 10,000,000 barrels per year. It was a district of great gushers (Fig. 48). The oil occurred near the crest of a sharp fault or fold in Cretaceous limestone. The crude oil was a heavy paraffin variety from which some gasoline and kerosene were obtained. Most of it was used for fuel. Over parts of this district oil seepages were numerous. (See Figs. 49 and 50.)

Tehuantepec, in the southern part of the country, is in

[116] Huntley, L. G., "The Mexican Oil Fields," Am. Inst. Min. Eng., *Trans.*, Vol. 52, pp. 281–321, 1915.
"Government Report on Mexico," *Oildom*, Nov. 21, 1921, p. 22.

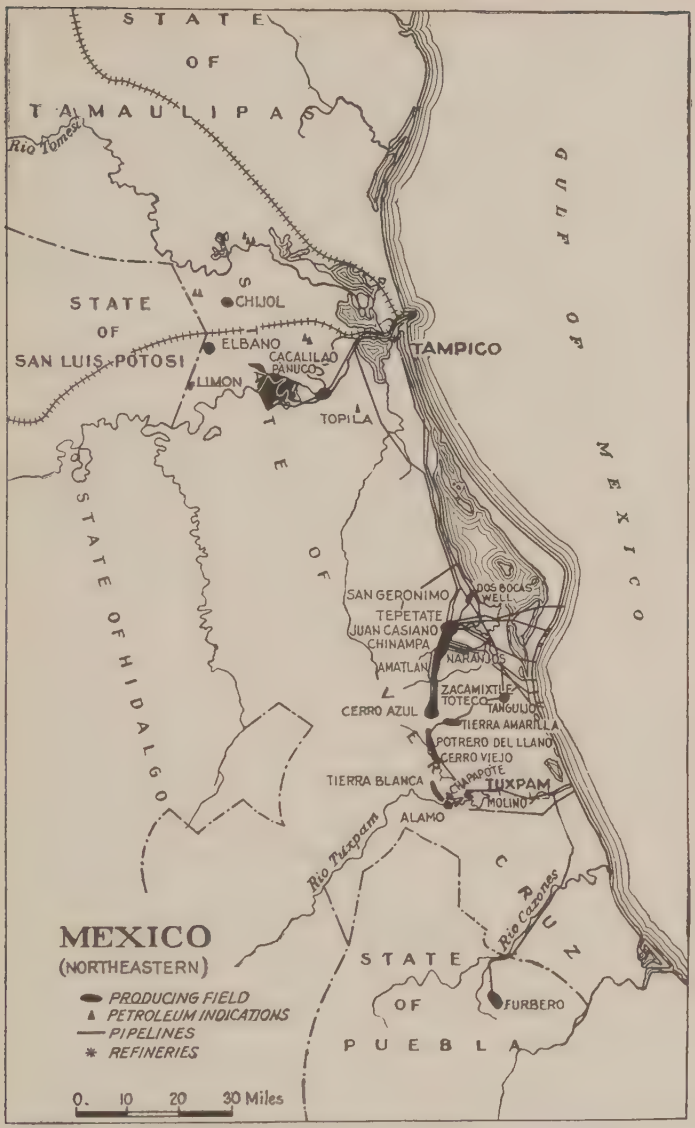


FIG. 47.—Map of Northeastern Mexico, showing positions of important producing oil fields. (*After Garfias, Petroleum Resources of the World.*)

the isthmus of that name. The oil is of high grade. It occurs around salt domes in Tertiary rocks.

FIG. 48.—The Cerro Azul, No. 4, a gusher in the Huasteca fields, Mexico. This well completed in February, 1916, yielded 260,858 bbls. of oil in the 24 hours before being closed in. (*Courtesy of the Pan-American Petro. and Transp. Co.*)

Canada.—In Canada commercial deposits have been developed in Ontario and Alberta and to a very small extent in New Brunswick, but not much oil has thus far

FIG. 49.—Seepage of thick oil near Cerro Pelon, in Huasteca fields, Mexico. The exudation of the oil is from fractures in sedimentary rocks shattered near a dyke. (*Courtesy of the Pan-American Petro. and Transp. Co.*)

FIG. 50.—Oil seepage near well No. 5, Cerro Azul. (*Courtesy of the Pan-American Petro. and Transp. Co.*)

been produced. The Ontario field is in Ordovician, Silurian and Devonian limestone between Lakes Erie and Huron.[117] The oil resembles that of the Lima-Indiana district in the United States. Oil is known to occur also at a number of places in western Canada and Nova Scotia.

Perhaps the most promising districts[118] in the Dominion are in the Upper Paleozoic beds along the foothills in western Alberta and in the valley of the Mackenzie River in the western portion of Mackenzie.

In the valley of the Athabasca River in Alberta, 2,000 square miles are covered with 50 to 175 feet of Cretaceous sands saturated with tarry petroleum (Fig. 51). These may prove to be a valuable source of oil, since an acre of the sand 50 feet thick contains 80,000 barrels of petroleum carrying more than 50% of kerosene and gasoline. In southwestern Alberta oil and gas wells have been obtained in a narrow strip of closely folded and faulted beds just east of the Rocky Mountains. The oil is crude naphtha, and the gas a "wet" gas from which large quantities of naphtha were condensed. Most of the yield is from Cretaceous and Paleozoic beds.

Although much money has been expended in trying to develop commercial fields in Western Canada, the ventures have not yet been attended with profit,[119] except in the Turner Valley.

Eur-asia.—A very small part of the great continent of Eur-asia has been explored for oil. It is known that oil indications exist at a number of places in Asia, but conditions have not been favorable for their thorough testing.

[117] Malcolm, W., "The Oil and Gas Fields of Ontario and Quebec," Geol. Sur. of Canada, *Mem.* 81, 1915.

[118] Clapp, F. G., and others, *Petroleum and Natural Gas Resources of Canada*, Depart. of Mines, Mines Br., 2 Vols., No. 291, 1914, 1915.

[119] McLean, F. H., and Hume, G. S., "The Stratigraphy and Oil Prospects of Alberta, Canada," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 237–260, 1927.

Russia.—In Russia[120] the principal producing districts are (Fig. 52):

Baku, along the southwestern shores of the Caspian Sea, at the southeast end of the Caucasus Mountains;

FIG. 51.—Sketch map showing positions of oil and gas fields and tar sands in Canada. (*After Clapp, Dept. of Mines (Canada), Mines Br. Pub. 291.*)

Grozny, along the northern flanks of the Caucasus, about 280 miles northwest of Baku;

Emba, on the northeast shore of the Caspian Sea;

Maikop, on the northern flanks of the Caucasus, 300 miles west of Grozny;

[120] Thompson, A. B., "Oil Fields of Russia," *Oil News*, Oct. 5, 1920, p. 20 and Oct. 20, 1920, p. 26.

Dalton, L. V., "A Sketch of the Geology of the Baku and European Oil Fields," *Econ. Geol.*, Vol. 4, pp. 89–117, 1909, and discussion by Huntley, Vol. 11, pp. 279–283, 1916.

Thompson, A. B., *Oil Fields of Russia and the Russian Petroleum Industry*, p. 522. New York.

Tcheleken Island, about 170 miles east of Baku, near the east end of the Caspian Sea;

Ferghana, in Turkestan, 800 miles east of Baku, and

Sakhalin Island, off the east coast of Siberia, now in the possession of the Japanese.

Formerly Russia produced from these fields about 85,000,000 barrels of crude oil, but after the war production fell off because of neglect of the wells, although now it has again reached this figure. There is no doubt of the abundance of oil still in the ground.

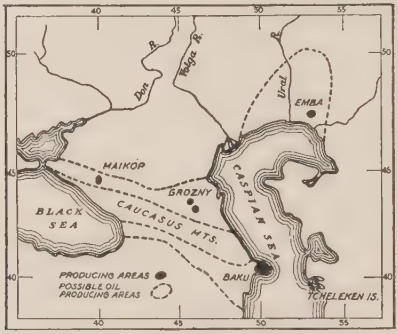


FIG. 52.—Sketch map showing positions of principal producing oil fields in Russia. (*After Lilley, The Oil Industry. D. Van Nostrand Co., N. Y., 1926.*)

The oil rocks in the Baku district are mainly Pliocene and Miocene, but some of the deeper wells penetrate the Oligocene. The traps are anticlines modified by cross folding and faulting. The district, although having an area of only 12 square miles, is noted for its great gushers, among which was the Droojba well which flowed at the rate of 50,000 barrels daily during its early life. Other wells had initial flows of 100,000 barrels daily, and another averaged 10,000 barrels daily for one year. The oil of the district is rich in the gasoline and kerosene fractions.

The area of the Grozny district is only 6,670 acres, but its production is only a little less than half that of the

Baku district. The oil which comes from the flat limb of a faulted dome of Miocene rocks is a paraffin oil characterized by a large content of lubricating fraction and a fair content of the gasoline and kerosene fractions.

The Emba district covers about 60,000 square miles, but most of this area has not been thoroughly explored. So far as known the rocks furnishing the oil are Jurassic or Permian in age. The wells are shallow and the oil is rich in lubricating fractions. The presence of massive bodies of salt and gypsum disclosed by drilling suggests the existence of salt domes.

The Maikop district is restricted in its proven area. The oil comes from gently folded Oligocene and Miocene beds. The average oil from this district is rich in kerosene and lubricating fractions, though a wide difference is noted in the product of different wells, shallower wells producing paraffin oil and some deep ones asphaltic oil.

The Tcheleken district is a dome in Middle Tertiary beds. The oil has a paraffin base which has sealed faults with ozokerite.

The Ferghana district is a small producer of a paraffin oil which is consumed locally. There are two oil horizons, one each in Cretaceous and Lower Tertiary rocks, and there are large deposits of ozokerite.

The oil deposits on Sakhalin Island are in folded Pliocene beds near the east coast of its northern half. The oil is heavy and is rich in lubricating fractions.

All the oil thus far produced in Russia is of high grade. There are many other portions of the country in which oil is known to exist, but very little exploration has been undertaken in areas outside of those named above. It seems certain, however, that Russia is destined before long to be one of the most important producing countries in the world.[121]

[121] Redfield, A. H., "The Petroleum Resources of Russia," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 493–513, 1927.

Persia.—In Persia the prospects for oil are very promising. Nearly all the production at present comes from Miocene rocks in the neighborhood of Schuster, from 100 to 140 miles from the head of the Persian Gulf. Some of the wells have flowed for many years and are still steady producers. The oil is of paraffin base and is rich in kerosene and lubricating fractions. Indications are promising for the extension of the producing area around Schuster and for the development of other areas in northern Persia. It is said that it was the desire to control the oil resources of this country that caused the agreement between Russia and England not to trespass on each other's spheres of influence in Persia.[122]

Dutch East Indies.—The Dutch East Indies include the islands of Sumatra and Java, the southern part of Borneo, and many small islands in the Malay Archipelago. Of the production in this area about 65% comes from Borneo, 22% from Sumatra, 11% from Java and 2% from Ceram. In Borneo all the oil is obtained from folded upper Tertiary rocks, over an average area of 500 square miles, of which only a comparatively small portion has been thoroughly explored. The oil from shallow wells is a heavy oil with an asphalt base; that from the deeper wells is a comparatively light oil with a paraffin base. Some of it is particularly rich in gasoline and kerosene (Fig. 53).

In Sumatra there are two producing fields in Miocene and Pliocene beds folded into steep anticlines. The Sumatra oil is particularly high grade.

In Java the producing area is the northern part of the island in Miocene sands along anticlines. The wells are shallow, their average yield is small but very steady, and their oil is high grade with a paraffin base.

Rumania.—The petroleum fields of Rumania are in a

[122] See *Oil and Gas Jour.*, Dec. 29, 1927, p. 155.

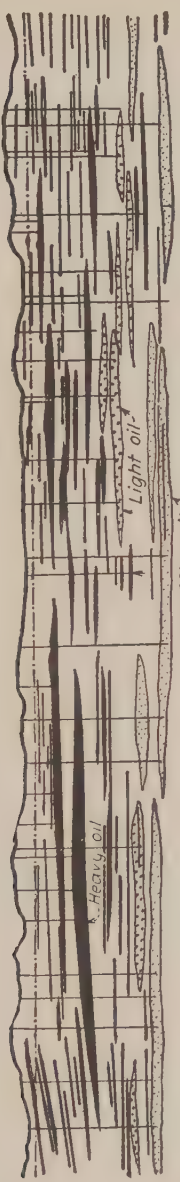


FIG. 53.—Longitudinal profile of anticline showing relative positions of lenses containing heavy (black) and light (dotted) oils. Small dots closely spaced indicate light oils with paraffin base. (*After Jezler. From Emmons: General Economic Geology, p. 191.*)

belt 15 to 20 miles wide and 259 miles long paralleling the Carpathian Mountains on their east and south sides.[123] The district is the oldest developed oil district in the world. The oil is in Pliocene and Miocene rocks that are steeply folded, faulted and intruded by plugs of salt, like those of the Gulf Coastal plain in the United States. About 40 such domes are known to exist but most of them have not been explored. The oil is of various grades with specific gravities ranging from .773 to .923.

Other fields in Eur-asia.—Among the remaining oil-producing districts in Eur-asia those in Galicia along the northern flanks of the Carpathian Mountains in Poland, those in Mesopotamia and those in India are the most promising.

The oil in Galicia is mainly in Cretaceous and Tertiary rocks. Oils with a paraffin base occur in Miocene and Eocene beds, while a small production of oil with an asphalt base comes from Cretaceous and older Tertiary beds. The pools are in complex anticlines, in some places near over-thrust faults of older sediments and in other places in salt domes. Most of the Galician oil is of high grade, containing from 49% to 63% of gasoline and kerosene fractions.

Mesopotamia is at present more interesting as a prospective oil producer than for its present production. It has a short coast line on the Persian Gulf and much of the activity in the neighborhood of the Persian Gulf is directed toward the development of the Mesopotamian deposits.

Only a small quantity of oil has been obtained from this district hitherto, but it has been known to exist at several places even since biblical times. The prospective fields of most promise are a stretch of territory extending from Mosul southeastward to Baghdad and a strip in the valley

[123] Mason, S. L., "Rumanian Oil Fields," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 9, pp. 145–157, 1925.

of the Euphrates from Hit to El Deir. The petroleum occurs in Miocene rocks and in deposits of asphalt. Most of the oil has an asphalt base and is of medium grade, but that in the neighborhood of Mosul is a light oil. It may be of interest to know that much of the production until recently has come from springs and from asphalt pools. Incidentally about 175,000 barrels of asphalt are produced annually.

Most of the Indian oil comes from Burma.[124] It occurs mainly in gently folded anticlines near the center of the synclinal trough of Tertiary rocks forming the great basin of Central Burma in which flow the Sittang and Chindwin-Irrawaddy rivers. There are now nine producing fields in which the oil horizons are near-shore marine deposits of later Eocene and Peguan (Miocene) ages.

South America.—South America has not yet been thoroughly explored with respect to its oil resources, though there are indications of the presence of oil in all parts of the continent that have been penetrated by white men (Fig. 54). Oil has been produced in Peru, Venezuela, Argentina, Trinidad and Colombia, but until recently in comparatively small quantities only. Within the past five years, however, extensive explorations have been undertaken by American interests in Venezuela and Colombia, and these countries are becoming of importance in the world's petroleum trade. Bolivia also is being explored with the promise of yielding satisfactory results.[125]

South America offers a promising field for exploration by American capital, but because of the difficulty of penetrating its interior, the exploration must be left to com-

[124] Stamp, L. D., "The Conditions Governing the Occurrence of Oil in Burma," Inst. Petr. Tech. (London), *Jour.*, Vol. 13, pp. 21-70, 1927, and "Geology of the Oil Fields in Burma," Am. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 557–580, 1927.

[125] Barth, E., "Petroleum Resources of Bolivia," *Oil and Gas Jour.*, Sept. 22, 1927, pp. 404–406.

panies that are financially able to invest large sums of money in opening up the country before hoping to obtain any adequate returns.

FIG. 54.—Sketch map of South America, showing positions of oil fields and districts showing oil indications. (*After Garfias, Petroleum Resources of the World.*)

Peru.—In Peru are three fields, the Negritos, the Lobitos and the Zorritos, all in the northwest corner of the country. In the Negritos field, which is the southernmost, the oil is in Eocene sands along an anticline complicated

by faulting. The crude oil is very much like that of Pennsylvania. The oils of the Lobitos and the Torritos fields are similar to that produced at Negritos.

Argentina.—The Argentina fields are near the coast about 1,000 miles south of Buenos Aires, where a small area has yielded oil from Cretaceous sands. The oil is heavy. About 10% of light fractions are recovered in the refineries, the other 90% being used for fuel. Some oil is known to occur also in the northwestern part of the country.[126]

Colombia.—In Colombia[127] only one important field has been discovered. This is near the center of the country, in the Upper Magdalena Valley, a short distance north of Bogota. The oil, which is of asphalt base, is of excellent grade. It occurs in faulted anticlines of Cretaceous and Tertiary beds, the older series being characterized by the presence of dark, bituminous shales and limestones. Seepages of oil from Cretaceous and Eocene rocks in the coastal region west of Lake Maracaibo suggest that this may also be a region in which oil deposits will be found.

Trinidad.—The production of Trinidad[128] is about 2,500,000 barrels annually, all from the southern portion of the island and most of it from within 25 miles of the great pitch lake, where it has accumulated in anticlinal folds of Miocene rocks. In the center of the island are other pools in Eocene sands. Here the oil is high grade, containing but 7% of fuel oil fraction.

Venezuela.—Venezuela at present appears to afford

[126] Anderson, R., "Observations on the Occurrence and Origin of Petroleum in Argentina and Bolivia," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 10, pp. 853–859, 1926.

[127] Garner, A. H., "General Oil Geology of Colombia," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 151–156, 1927.

[128] Waring, G. A., "The Geology of the Island of Trinidad, B. W. I." The Johns Hopkins Univ., *Studies in Geol.*, No. 7, 1926.

Liddle, R. A., *The Geology of Venezuela and Trinidad.* Fort Worth, Texas, 1928.

promise of becoming one of the world's most important producers of high grade petroleum. In Venezuela[129] there are nine or ten distinct fields, of which the Mene Grande, which is located on an anticline on the east side of Lake Maracaibo, about 12 miles from its shore, and about 70 miles southeast of Maracaibo, the La Rosa, on the east shore of the lake about 27 miles from Maracaibo and the Lagunillas also on the lake shore, about 25 miles south of La Rosa, are the most important at present. In the La

FIG. 55.—View of portion of producing field, Lake Maracaibo, Venezuela.

Rosa and Lagunillas fields many of the wells are in the lake (Fig. 55). The other fields, which have not yet been thoroughly developed, are the Ambrosio, a few miles north of the La Rosa, El Mene, in the hills, about 40 miles east of Maracaibo, La Conception, about 20 miles southwest of Maracaibo, La Paz, 12 miles northwest of La Conception, the Rio Palmar, 30 miles west-southwest of La Paz, the Rio de Oro, southwest of the Lake and about 135 miles southwest of Maracaibo, and La Tarra, 40 miles southeast of Rio de Oro. Other probable fields lie south of the Lake, since there are many oil seepages known to occur in the district.

[129] Hunter, C. M., "The Oil Fields of the Māracaibo Basin," Inst. Petrol. Tech. (London). *Jour.*, Vol. 12, pp. 235–256, 1926.

The rocks of the Maracaibo basin are Cretaceous and Tertiary, mainly sandy, beds gently folded into a great syncline 150 miles across, in the center of which is Maracaibo Lake.[130] The oils are in subordinate anticlines and in cross-folds superimposed on the great syncline. Heavy, asphaltic oils occur in the Tertiary beds and light, in part paraffin, oils in the older rocks. About 95% of the present production is of heavy oil. From the Miocene beds outcropping around the margins of the basin are seepages which are among the largest in the world.

It is probable that the field will continue to the west and southwest and that other fields will be developed in many other portions of the country where oil seepages and asphalt deposits are known to occur. From some of these asphalt has been exported for many years.[131]

WORLD'S PRODUCTION

The energetic search for oil in all corners of the world during the past decade has resulted in the discovery of many new oil-producing areas. The search is rapidly spreading so that before many years the list of important oil-producing countries will be materially lengthened and the relative positions in the list of those now producing will be changed. South America is just beginning to be explored and Africa has not yet been touched by serious explorers.[132]

[130] Liddle, R. A., "Tectonics of the Maracaibo Basin, Venezuela," Amer. Assoc. Petrol. Geol., *Bull.*, Vol. 11, pp. 177–186, 1927.

Hopkins, E. B., and Wasson, H. J., "Venezuela's Remarkable Development, Challenging Mexico as Third Oil-producing Country," *Oil and Gas Jour.*, pp. 49, 94–96, Dec. 29, 1927.

[131] Liddle, R. A., *The Geology of Venezuela and Trinidad*, p. 552, pl. 33, Figs. 21 and Map. Fort Worth, Texas, 1928.

[132] For account of the distribution of the oil fields of the world a few years ago, see Garfias, V. R., *Petroleum Resources of the World.* New York, 1923, and Report III of the Federal Oil Conservation Board to the President of the United States, Feb. 25, 1929. Office of the Board, Interior Department Building, Washington, 1929.

For a general discussion of all phases of the petroleum industry see Sir B. Redwood: *Treatise on Petroleum*, 3 Vols., 4th Ed., London.

The production of the world in 1927, as shown in the following table, was about one-twelfth of the total production for the 70 years since oil was first produced.

TABLE XXII.—WORLD'S ESTIMATED PRODUCTION OF PETROLEUM IN 1927 AND TOTAL PRODUCTION, 1857–1927

Country	1857–1927 *Thousands of Barrels of 42 U. S. Gallons*	*Rank* 1857–1927	1927 *Thousands of Barrels of 42 U. S. Gallons*	*Rank* 1927
United States	10,345,346	1	901,129	1
Russia	2,240,924	2	77,018	2
Mexico	1,471,417	3	64,121	3
Dutch E. Indies	356,269	4	25,967	7
Rumania	315,780	5	26,368	6
Persia	257,499	6	39,688	5
Poland (Galicia)	208,337	7	5,342	13
India	181,552	8	7,878	11
Venezuela	139,392	9	63,134	4
Peru	83,267	10	10,135	9
Japan and Taiwan	54,997	11	1,700	15
Argentina	42,186	12	8,630	10
Trinidad	38,596	13	5,712	12
British Borneo (Sarawak)	30,704	14	4,943	14
Canada	26,747	15	477	20
Colombia	22,817	16	15,002	8
Germany	18,503	17	663	17
Egypt	15,315	18	1,267	16
Ecuador	.....	..	537	18
France	4,204	19	504	19
Sakhalin	.....	..	440	21
Italy	1,231	20	(*a*)	..
Czechoslovakia	938	21	149	22
Others	1,971	..	269	..
TOTAL	15,810,336		1,261,073	

(*a*) Included under "Others."

CARBON BLACK

Carbon black is the soot produced by the partial combustion of natural gas. It is therefore made in largest quantity where the supply of gas is greatest. There are 65 plants working in the United States, the greatest number of which are in Louisiana, Texas and Wyoming. Their average yield is about 1.4 lbs. per 1,000 feet of gas consumed, and the aggregate yield in 1928 was about 248,790,000 lbs., valued at about $13,782,000 or 5.54 cents per lb. About 175,137,000,000 cu. ft. of natural gas were burned, producing 1.42 lbs. of carbon black per 1,000 cu. ft.

The material is used in printer's ink, in rubber tires to increase wearing power and diminish slipping, in varnishes and enamels, in stove and shoe polish, in buttons, to surface carbon paper and typewriter ribbons, and in the manufacture of phonograph records and many other articles. In 1925 the rubber tire industry consumed about 49.2% of the production, printer's ink about 12.7%, varnishes and paints about 6.7% and other items about 6.8%. The balance, 24.6%, was exported. In 1928 the exports aggregated 77,903,153 lbs., valued at $6,794,224. Most of it went to the United Kingdom, France and Germany.

CHAPTER V

SOLID AND SEMI-SOLID BITUMENS

Solid and semi-solid bitumens, some of which are related to petroleum and others possibly to coal may be grouped as:

1. Bitumens or asphaltites, solid materials filling fissures in rocks or occupying basin-like depressions, and
2. Ozokerite, solid paraffin.
3. Malthas, viscous materials oozing from rock fissures or constituting pools.

They are of various characters and are utilized for very many purposes.

Asphaltites.—The vein bitumens are black or brown, pitchy in odor, burning with a smoky flame and soluble to different degrees in ether, turpentine and naphtha. They are probably all derived from petroleum [1] by devolatilization and more or less oxidation.

They include albertite, grahamite, gilsonite, wurtzilite and lake asphalt.

Albertite.—Albertite is a black, dense, lustrous bitumen with a conchoidal fracture and a specific gravity of 1.097. It is fairly soluble in turpentine, but is insoluble in alcohol. Its most noted occurrence is at the Albert Mines in New Brunswick, where it forms a vein in subcarboniferous shales.

Grahamite.—Grahamite is a pitch-black bitumen, soluble in turpentine, carbon bisulphide and chloroform. Its

[1] Eldridge, G. H., "The Formation of Asphalt Veins," *Econ. Geol.*, Vol. 1, pp. 437–444, 1905–6.

specific gravity is 1.145. It is found in veins in West Virginia (Fig. 56), Arkansas, Oklahoma and elsewhere, where it appears to have been formed by the oxidation of slowly seeping asphaltic petroleum.[2]

FIG. 56. Map showing relation of grahamite fissure of Ritchie County, W. Va., to Burning-Springs-Eureka anticline. (*After I. C. White, Bull. Geol. Soc. Amer., Vol. X.*)

Analyses of two grahamites are as follows:

	Volatile	*Fixed Carbon*	*Ash*	*S.*	*Moist*
Jimpson Valley, Okla.	43.33	55.97	1.45	1.47	.25
Fourche Mountain, Ark.	17.78	79.15	.56	1.38	2.50

[2] White, I. C., "Origin of Grahamite," Geol. Soc. Amer., *Bull.* Vol. 10, pp. 277–284, 1899.

Gilsonite.—Gilsonite, or uintaite, is a black, brilliant bitumen, with a conchoidal fracture and a specific gravity of 1.07. It is partly soluble in alcohol and ether and completely soluble in chloroform and warm turpentine. It occurs in veins in northeastern Utah and western Colorado. The manjak of Trinidad and Barbados may be the same thing.[3]

Gilsonite is used for making varnishes for iron work and

FIG. 57.—General view of asphalt lake, Brighton, Trinidad. (*Courtesy of the Barber Asphalt Company.*)

for baking Japans, for coating masonry and chemical tanks, as a substitute for carbon black, especially in automobile tires and garden hose, and as a binder pitch for coal briquettes.

Wurtzilite.—Wurtzilite, or elaterite, is an elastic, sectile, pitch-like bitumen with a petroleum odor. It fills fissures in the rocks of the Uinta Basin, Utah. Its specific gravity is 1.03. It is used in the manufacture of paint, roofing material, waterproof felt, rubber substitutes, building paper and paving materials.

[3] Eldridge, G. H., "The Uintaite (Gilsonite) Deposits of Utah," U. S. Geol. Sur., *17th Ann. Report*, Pt. I, pp. 909–949, 1896.

Asphalt.—Lake asphalt is the natural pitch occurring in the Pitch Lake of Trinidad off the Venezuela Coast. It occupies about 100 acres of area. The top is hard, like pitch, but under the crust the material is soft (Fig. 57). This differs from ordinary malthas in that it hardens

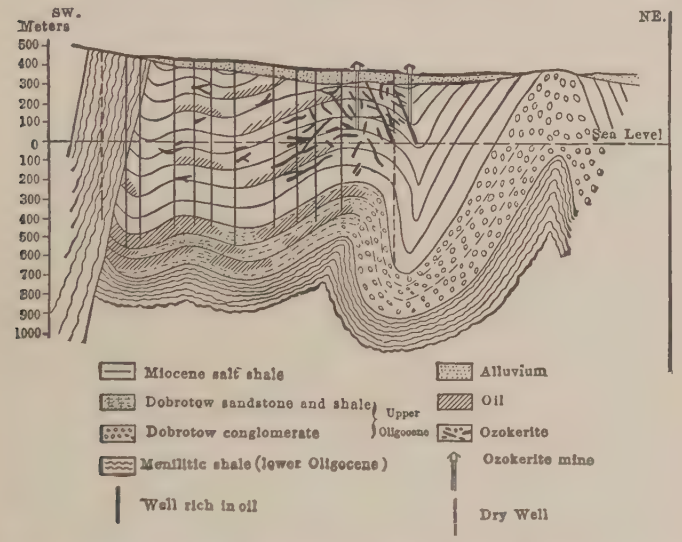


FIG. 58.—Profile through Boryslaw oil field, Galicia, showing ozokerite dikes near crests of anticlines. Horizontal and vertical scales the same. (*After Zuber. From Emmons: General Economic Geology, p. 199.*)

rapidly, and therefore is an excellent road material when mixed with sand.

OZOKERITE.—All the preceding materials are residual products of asphaltic petroleum. Ozokerite is the residuum of paraffin oil. It is a yellow, brown or green translucent paraffin with a specific gravity near .90. It is soluble in petroleum, turpentine and carbon bisulphide, but is only partially soluble in ether. It occurs in crushed Tertiary shales in Utah [4] and in rocks of recent age in

[4] Robinson, H. M., "Ozokerite in Central Utah," U. S. Geol. Sur., *Bull.* 641, Pt. II, pp. 1–16, 1916.

many parts of Eur-asia, the largest deposits being in Galicia (Fig. 58). When refined it is known as ceresin in which form, because of its comparatively high melting point, it is used in making candles, ointments and bottles, and as an adulterant in beeswax and in the manufacture of polishes. It is used also as an acid-proof backing for electrotyper's plates, as a component in the manufacture

FIG. 59.—Quarry of bituminous sandstone, Santa Cruz. (*After Eldridge, U. S. Geol. Sur., 22nd Ann. Rep.*)

of phonograph records, as a source of illuminating gas, oils, etc., as an insulator of electricity and as a covering to protect metal surfaces. Its principal use, however, is as a substitute for paraffin in coating waxed wrapping paper.

MALTHAS.—Liquid asphaltic material, or maltha, occurs to a slight extent in California and Texas where it issues from crevices in the rocks overlying asphaltic oils. As these seep to the surface, they lose on exposure to the air their more volatile components, suffer some oxidation and leave a residue very much like the tar produced by distillation of oil.

Most of the maltha produced in this country is the tarry substance left as the final residue after distillation of the asphaltic oils of California, Illinois and Oklahoma and of oil imported from Mexico. It is used mainly for waterproofing foundations and in road-making.

Bituminous rocks.—Much of the natural bitumen used in the United States is in the form of rocks saturated

Fig. 60.—Map of bitumens and bituminous rocks in the United States. (*After Eldridge, U. S. Geol. Sur., 22nd Ann. Rep.*)

with bituminous matter, mainly of asphaltic character. In some the bituminous substance is maltha, in others genuine asphalt. For paving purposes only the latter is of value, and its content of bitumen must be at least 7%. In California (Fig. 59), bituminous shales and sandstones are worked, in Oklahoma bituminous sandstones and limestones, in Kentucky bituminous sandstones, and in Texas and Alabama bituminous limestones[5] (Fig. 60). In Europe bituminous limestones have been mined at a number of

[5] Clark, G. H., "Rock Asphalts of Alabama and Their Use in Paving," *Geol. Sur. of Alabama*, 1925.

places, and in Canada it is proposed to use the bituminous sand of Alberta for surfacing roads.[6] (See p. 144.)

COMPOSITION

The composition of the various types of asphaltites and malthas is shown by the following analyses quoted from Ries.

TABLE XXIII.—ULTIMATE ANALYSES OF BITUMENS

	C	H	N	O	S	Ash
Grahamite, W. Va.	59.20	5.77	1.01	14.68	....	19.34
Gilsonite, Utah	89.28	8.66	.79	....	1.79	....
Wurtzilite, Utah	80.00	12.23	1.78	....	5.83	....
Albertite, N. S.	86.04	8.96	2.93	1.97	Tr.	.10
Lake Pitch, Trinidad	83.68	10.84	.45	....	5.10	....
Maltha, Calif.	85.72	11.83	1.21	....	1.32	....
Ozokerite, Utah	85.25	15.09	....	....	....	....

PRODUCTION AND USES

The quantity of bituminous material produced in the United States during 1927 was:

TABLE XXIV.—PRODUCTION OF BITUMENS IN THE UNITED STATES—1927

	Tons	*Value*
Gilsonite	42,580	$ 876,820
Wurtzilite	280	24,750
Ozokerite	80	32,000
Grahamite	..	...
Bituminous rock	796,100	4,672,280
TOTAL NATIVE BITUMENS	839,040	$5,605,850
Petroleum asphalt (manufactured)	1,525,420	$19,019,150
TOTAL OF DOMESTIC MATERIAL	2,364,460	$24,625,000

[6] Ells, S. C., "Use of Alberta Bituminous Sands for Surfacing Highways," Can. Dept. of Mines, Mines Br., *Pub.* 684, 1927.

All of the asphaltites produced in the United States came from Utah; the bituminous rock from Texas, Kentucky, Oklahoma, Alabama, and California.

In 1927, additional asphalt was manufactured from Mexican and Venezuelan petroleum amounting to 2,426,030 tons valued at $35,771,940, making the total of manufactured asphalt 3,951,450 tons valued at $54,791,090.

The uses of the asphalt manufactured from petroleum were:

TABLE XXV.—USES OF MANUFACTURED ASPHALT IN 1927

	Short Tons	*Value*
Paving	1,881,900	$28,246,180
Roofing and water-proofing	1,302,500	17,429,470
Mineral rubber	20,910	330,930
Road oil	297,110	3,129,520
Other	448,880	5,654,990
TOTAL	3,951,450	$54,791,090

IMPORTS AND EXPORTS

The imports during 1927 were: native asphalt and bituminous rock, 158,097 tons, valued at $1,140,425, of which 85,038 tons, valued at $626,566, were from Trinidad and 66,254 tons, valued at $437,744, were from Venezuela.

The imports of ozokerite were 3,800 short tons, valued at $579,118, mostly from Boryslaw, Galicia.

The exports were 39,875 short tons of native asphalt with a value of $1,034,334, and manufactured material valued at $2,399,700, besides 385,031 tons of petroleum asphalt valued at $8,325,413.

OCCURRENCES

The largest deposits of ozokerite are in Galicia, of grahamite in Cuba, of gilsonite in Utah, of albertite in

New Brunswick, and of asphalt and related bitumens in Trinidad, Venezuela, France, Germany, Italy, Russia, Spain, Japan and Asiatic Turkey. Some of them have been exploited from the earliest times, but only in Trinidad, Italy, Germany and Venezuela are they now being worked on a large scale. Bituminous rocks occur in many countries.[7] In Alberta,[8] Canada, along the Athabasca River, is an area of over 750 square miles underlain by a thick layer of sand lying between Devonian limestone and Cretaceous sandstones and shales. Different samples have been found to contain from 1 to 17.5% of bitumen.

[7] Eldridge, G. H., "Origin and Distribution of Asphalt and Bituminous Rock Deposits in the United States," U. S. Geol. Sur., *Bull.* 213, pp. 296–305, 1903.

Abraham, H., *Asphalt and Allied Substances: their occurrence, etc.*, 2nd Ed., New York, 1929.

Osborne, C. C., "Asphalt and Allied Substances," U. S. Geol. Sur., *Min. Res. 1918*, Pt. II, pp. 447–494, 1921.

[8] Ells, S. C., "Bituminous Sands of Northern Alberta," Can. Dept. of Mines, Mines Br., *Pub.* 632, 1926.

CHAPTER VI

OIL SHALES

Since it is possible that the petroleum supply will not be adequate for the needs of industry after a few years, it becomes important to consider other sources of supply for the motor and illuminating oils that are now so necessary to civilization.

Although it is realized that coal may be made to furnish a supply of petroleum (see pp. 228–229), when the price of this commodity increases sufficiently to warrant its manufacture from lignitic and cannel coals,[1] the "oil shales," at present, seem to offer the best promise to supply the need.

Definition.—Oil shales are compact sedimentary rocks, usually finely laminated, that contain organic matter which yields oil upon distillation. This material is termed "kerogen." In addition to kerogen many shales contain bituminous substances that yield hydrocarbons upon extraction by solvents. This soluble component exists in the shale as petroleum constituents, but in the true oil shales there is little of the soluble component, the "shale-oil" being produced only by the destructive distillation of the kerogen. Oil shales thus differ from bituminous rocks in that the latter contain petroleum or petroleum residues already formed.

RELATION TO COALS

Oil shales may be regarded as cannel coals containing a very large quantity of ash, which is mainly clay and fine

[1] Craig, E. H. C., "Jet and Jetonized Material," Inst. Petrol. Tech. (London). *Jour.*, Vol. 13, pp. 343–362, 1927.

sand. The kerogen occurs as small yellow, brown or black, globular masses, believed to be spores of fernlike plants, or as irregular streaks scattered through the inorganic matrix which has the general appearance of an ordinary shale (Fig. 61). In addition to these substances most oil shales contain small quantities of pyrite, pyrrhotite and gypsum, which are objectionable because during the process of distillation they yield H_2S which goes over

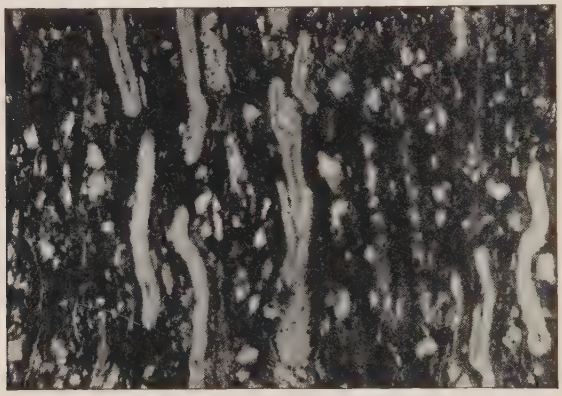


FIG. 61.—Microphotograph of black shale from Blocker, Ind., showing collapsed spores. Irregular white spots are clay particles. The darker areas are finely macerated organic matter. (*After Thiessen, Economic Geology, Vol. 16.*)

with the distillate. Some of the H_2S that is produced when the shale is heated comes off at a low temperature. This, it is believed, is due to the decomposition of sulphur-bearing carbon compounds.

Thiessen[2] finds that the oil shales of the Mississippi Valley are characterized by large numbers of spores embedded in a fine groundmass made up of fragments of spores, and a dark-colored organic matter consisting of fragments of leaf cuticles and a groundmass of finer grain

[2] Thiessen, R., "Origin and Composition of Certain Oil Shales," *Econ. Geol.*, Vol. 16, pp. 289–300, 1921.

the nature of which cannot be determined. (See Figs. 61, 63 and 64.) It is worthy of notice that the oil shales described by Thiessen contain no animal matter. In all essential respects they are like the Scotch shale that has been used as a source of oil for many years. On the other hand, there are other shales, having a different geological history, that are quite different from the Mississippi Valley shales in composition, structure and physical characters, as for example those in Colorado, Utah and Nevada, and these it is thought would yield distillation products that will differ from those of the Scotch shale.

COMPOSITION AND ORIGIN

The proximate analyses of some well-known foreign oil shales and of a few from this country are shown below.

TABLE XXVI.—PROXIMATE ANALYSES OF SOME OIL SHALES

	Moist.	*Volatile*	*Fixed Carbon*	*Ash*
Dunnet Seam, Scotland	6.47	19.25	8.37	65.91
Jubilee Seam, Scotland	1.92	22.41	1.81	73.86
Hartley, Australia	1.02	75.20	15.30	8.48
Hartley, Australia	.85	45.32	31.27	22.56
Elko, Nevada	2.40	29.3	4.2	64.4
New Albany, Ind	.85	15.86	5.54	77.78

The nitrogen content of oil shales is of great interest because it is a necessary component of ammonium sulphate, which is one of the most important by-products of their distillation. In American shales the nitrogen is apparently in combination with the kerogen, since it increases with the oil yield. In Scottish shales it is probably in some other form since it varies inversely as the oil yield.

A few of these relations are shown below:

TABLE XXVII.—NITROGEN CONTENT OF REPRESENTATIVE AMERICAN OIL SHALES

Shale	*Nitrogen Per Cent*	*Equivalent Am_2SO_4 (Lbs. per Ton)*	*Oil Yield (Gals. per Ton)*
Elko, Nev.	0.43	40.5	32.52
Soldier Summit, Utah	.58	54.7	44.60
Green River, Wyom.	.35	33.0	23.45
Ione, Calif.	.39	36.8	52.00
DeBeque, Colo.	.96	90.5	60.15

A uniform relationship between nitrogen and oil exists, however, only between shales in the same general districts. Shales from different districts show different nitrogen-oil ratios. In the East, if Thiessen is correct, there is little animal matter in the shales; in the Rocky Mountain States, however, animal remains are not uncommon. It is probable that much of the nitrogen in the western shales comes from the animal matter, whereas in the eastern shales it must have some other source.

It is pretty generally agreed that the oil shales were laid down in fresh water swamps or lagoons and that the organic matter in them originated in the same way as that in cannel coals.[3]

SHALE-OIL

Shale-oil has been produced in Scotland for many years, and it was thought that the success of the industry in that country was evidence that shale-oil could also be produced in other countries on a commercial scale. It is now known, however, that the shales in different localities have indi-

[3] An excellent summary of our knowledge of oil shales can be found in a report by M. F. Gavin, "Oil Shale—An Historical, Technical and Economic Study," U. S. Bur. of Mines, *Bull.* 210, 1924.

vidual characteristics and that their successful treatment must be differently developed in each shale-producing locality to yield satisfactory results.[4]

In Scotland during 1916 the quantity of shale distilled was 3,500,000 tons yielding 80,500,000 gallons of crude oil, 27,500 tons of paraffin, and 59,400 tons of ammonium sulphate, besides a large quantity of gas that was used as fuel.

The yield from one ton of shale was:

Oil	24 gals.	Gas	2,000 ft.
Am_2SO_4	34 lbs.	Residues	1,600 lbs.

The cost of production was $2.00, and the value of the products was $2.80.

In 1919 the quantity of products finished per ton of shale treated was:

Naphtha	2.45 gals.	Wax	17.70 lbs.
Burning Oils	6.13 gals.	Coke	3.62 lbs.
Gas and Fuel Oils	5.88 gals.	Am_2SO_4	35.70 lbs.
Lubricating Oils	1.72 gals.		

The methods employed in Scotland for the production of oil from shales are probably quite different from those that will have to be employed in the United States because the nature of the organic content of shales from different sources differs. Moreover, the products will be different in the two countries and probably different in different portions of the United States.

If the crude oil obtained from different shales is different in character, the methods of refining must be different and the final marketable products will also be different in character and amounts. Consequently each shale-oil in-

[4] Karrick, L. C., "Manual of Testing Methods for Oil Shale and Shale Oil," U. S. Bur. Mines, *Bull.* 249, 1926.
Alderson, V. C., *The Oil-shale Industry.* New York, 1921.

stallation must have an individual character, being designed for the treatment of the shale which will be supplied to it. For this reason the industry must be of slow growth. It must be preceded by a large amount of experimentation on that particular kind of shale expected to be treated and the plant will have to be constructed in accordance with the results of this experimentation. Moreover, shale-oil plants are expensive to build. Gavin[5] has estimated that the investment necessary for a complete retorting and refining plant will approximate $3,000 per barrel of shale-oil daily capacity. To replace the present domestic output of petroleum with shale-oil would require 1,900 shale-retorting plants, each with a daily capacity of 1,600 tons of shale yielding 42 gallons of oil per ton. About 700,000,000 tons of shale would have to be mined—a larger tonnage than the average annual coal production, and the investment for retorts and refineries would be over $5,000,000,000, in addition to the cost of lands, of opening up and developing mines, and of financing transportation and marketing facilities; nor does this sum include the cost of establishing subsidiary industries without which a shale-oil industry could not exist.

The shale-oil industry will not offer opportunities for the production of sudden wealth. It can never be spectacular in its returns. It will have more the character of a manufacturing industry like the iron industry, than that of a mining industry in which wealth may sometimes be acquired rapidly. Profits will depend upon careful management rather than upon good fortune, and upon the success obtained in producing gasoline from shale-oil by a "cracking" process.[6]

[5] Gavin, M. J., l.c., p. 134.

[6] It has been estimated that there is enough oil shale in the United States to produce over 180,000,000,000 barrels of shale-oil and that this can be cracked to yield about 90,000,000,000 barrels of gasoline. See Morrell and Egloff: *Jour. Ind. and Eng. Chem.*, Vol. 17, p. 801, 1926.

OCCURRENCE OF OIL SHALES IN THE UNITED STATES

The most promising oil shales in the United States occur in Colorado, Nevada, Idaho, Utah, Wyoming and Montana (Fig. 62). Those of Montana are Upper Paleozoic, but the others are Eocene. Certain black shales in New York, Pennsylvania and in the Central States of the Mississippi Valley may also be potentially oil-producing. Most of these are Upper Devonian, but others are Lower

FIG. 62.—Map showing distribution of principal deposits of oil shales in the Rocky Mountain States. (*After Winchester, U. S. Geol. Sur., Bull. 729.*)

Devonian and Ordovician. The shales of California that may also be used as a supply of oil are not properly oil shales since their organic matter is mainly oil as such. These are Miocene.

The most valuable shales in the Rocky Mountain States are those of the Green River formation (Figs. 63 and 64) in northwestern Colorado, in southwestern Wyoming and northeastern Utah. According to Winchester[7] this forma-

[7] Winchester, D. E., "Oil Shale of the Rocky Mountain Region," U. S. Geol. Sur., *Bull.* 729, 1923.

tion contains persistent beds some of which are 49 feet thick and will yield from 35 to 60 gallons of oil and 20 lbs. of ammonium sulphate per ton. The oil-yielding shales in many places outcrop on the sides of steep walls of canyons being more resistant to weathering than the

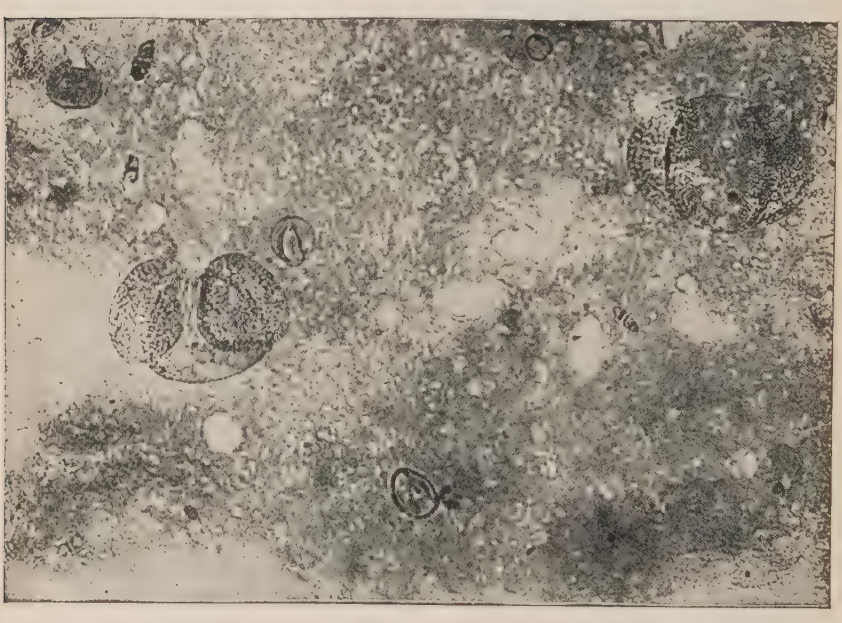


FIG. 63.—Microphotograph of fossil plant remains in oil shales of the Green River formation. x 245. (*After Winchester, Economic Geology, Vol. 12.*)

barren beds (Fig. 65). They are thus favorably situated for cheap mining.

The oil shales of Nevada are mainly in the eastern part of the State. The beds are thin and are folded and faulted and therefore do not afford as favorable conditions for mining as those in Colorado, Wyoming and Utah. The richest known bed is 4 feet thick. It yielded in an experimental run 32 gallons of oil per ton, and contains enough nitrogen to make 40.5 lbs. of ammonium sulphate per ton.

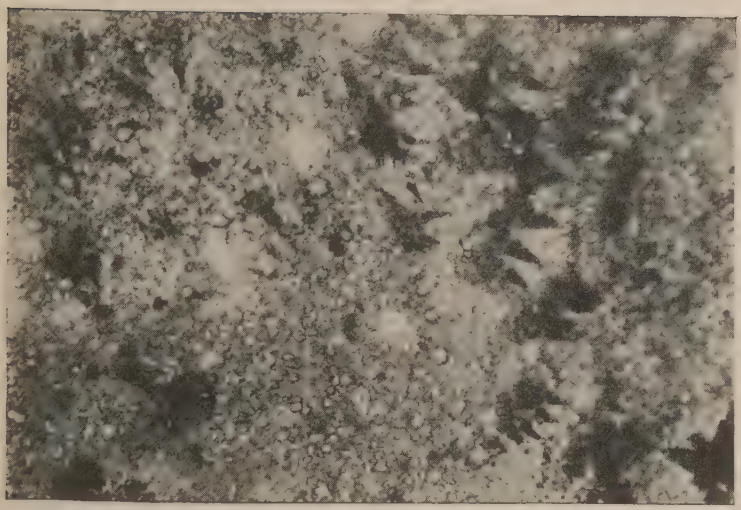


FIG. 64.—Microphotograph of Green River oil shale, showing dermal spines of fly larvæ. The light gray granular groundmass is a mixture of calcite, dolomite and pyrite grains, clay minerals and macerated organic substance. x 300. (*Courtesy of W. H. Bradley, U. S. Geol. Sur.*)

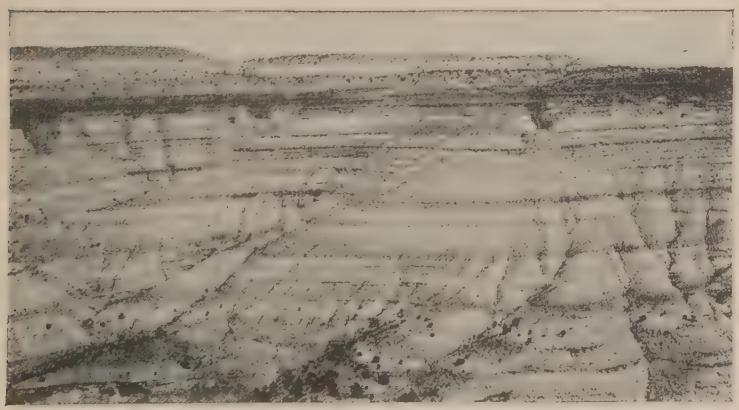


FIG. 65.—Green River formation, showing oil shales, northeast of Watson, Utah. Darker bands are richest beds. About 600 ft. of rock exposed. (*After Winchester, U. S. Geol. Sur., Bull. 729.*)

The oil shales of Montana[8] are partly in the Phosphoria formation, believed to be Permian, and partly in Tertiary beds. There are a few beds in the Phosphoria formation that will yield 30 gallons of oil per ton, but these are too thin to be workable. Other seams that are of workable thickness will yield 20 gallons of oil and 71 lbs. of ammonium sulphate per ton. The Permian shales are steeply dipping and are faulted, but they outcrop high on mountain sides and are therefore easily mined. The Tertiary shales are in long, narrow basins of moderate extent. Samples across zones 5 feet thick yield as much as 24 gallons of oil and 85 lbs. of ammonium sulphate per ton.

The California shales are in the Monterey formation. They are diatomaceous and when freshly broken smell strongly of petroleum. The richer shales yield about 20 gallons of oil per ton, but their nitrogen content is low.

The oil shales of the Mississippi Valley and of the Eastern States are not as rich in oil as those in the Rocky Mountain region but their great thickness and areal extent and the fact that they may be mined by inexpensive methods suggest that their development in many places is feasible. Samples of Kentucky shale yield 16 gallons of oil per ton and contain enough nitrogen to make 58.6 lbs. of ammonium sulphate per ton.

The oil produced from the Devonian shales of the East seems to be of a higher quality than that produced from many western shales, especially as to the amount and quality of the motor-fuel fraction.[9]

[8] Bowen, C. F., "Phosphatic Oil Shales, Near Dell and Dillow, Beaverhead County, Montana," *Ibid.*, *Bull.* 661, pp. 315–328, 1918, and

Condit, D. D., "Oil Shale in Western Montana, Southeastern Idaho and Adjacent Parts of Wyoming and Utah," *Ibid.*, *Bull.* 711, pp. 15–40, 1920.

[9] Ashley, G. H., "Oil Resources of Black Shales of the Eastern United States," U. S. Geol. Sur., *Bull.* 641, pp. 311–324, 1917.

Reeves, John R., "The New Albany Shale of Indiana," Bur. of Mines, *Reports of Investigations*, Serial No. 2390, Aug. 1922, and A section through the new Albany shale: *Idem*, Serial No. 2424, Dec. 1922.

The yield of oil and by-products from much of the oil shales in the United States is as great as that of the Scottish shales, consequently there would appear to be no reason why the shale-oil industry should not in time be developed as satisfactorily in America as in Europe. This, however, will probably not be the case until a scarcity of petroleum begins to be felt.[10]

No estimates have been made of the total volume of oil shale in the United States, nor is it known what average yield of oil would be required to make the shale-oil industry profitable. Winchester, however, concludes, as the result of his study of the Colorado shale, that in the area examined by him there is enough shale to produce 20,000,000,000 barrels of crude oil and 300,000,000 tons of ammonium sulphate, and that this amount of shale-oil would yield 2,000,000,000 barrels of gasoline. In the entire United States there are many times as much oil shale as there is in Colorado, so that the potential supply of oil in shales is enormous.

FOREIGN OCCURRENCES

Oil shale occurs in many parts of the world but its value as a source of oil is known only for a few deposits. The oil shale in Scotland is the best known. About 20 different Lower Carboniferous beds have been worked, but at present only about 10 are being operated. These range from 3½ to 10 feet in thickness. They occur in small basins and in many places they are badly faulted. In 1927 the production was 1,183,309 barrels of oil, obtained from 2,047,263 long tons of shale.

In Canada oil shales occur in New Brunswick, Nova Scotia, Quebec, Newfoundland and elsewhere, but most of the deposits have not been carefully examined. Some

[10] For a brief summary discussion of oil shales in the United States, see Winchester, D. E., *Econ. Geol.*, Vol. 12, pp. 505–518, 1917.

of the New Brunswick shale yielded, in the Scotch retorts, from 24 to 48 gallons of oil and 70 lbs. of ammonium sulphate per ton.

In England large quantities of oil shales are known in Dorset and around Norfolk. Experiments on Kimmeridge shale have yielded from 15 gallons to 42 gallons of oil per ton and 30 lbs. of ammonium sulphate.

In Jugoslavia some of the shales yield over 45 gallons of oil per ton and those in Switzerland about 15 gallons. In Bulgaria there are 30,000,000 tons of shale that will yield 13% of oil.

In France oil shales have been worked for many years yielding from 12 to 26 gallons per ton. In the Autun (Saône-et-Loire) district about 110,000 tons of shale are mined annually.

Oil shales are also being worked in Spain, Estonia and Brazil. In Spain they occur at a number of places but there are no data on the supply available. The deposit of Carboniferous age near Puertollana is now being mined and distilled, yielding 3,500 gallons of oil daily.

Estonia appears to have an enormous supply of shale, interlayered with limestone. One deposit in the north-eastern part of the country is said to contain about 1,500,000,000 tons of shale that will yield about 50 gallons of oil per ton.

The Brazilian shales are found in several provinces, the most important being in Sao Paulo where there are soft shales in Tertiary beds that yield from 25 to 30 gallons of oil per ton. Another shale in South Brazil is of Permian age. It is low grade, but is about 100 feet thick and is easily mined.

In all three of these countries, shale is being mined, but its distillation is still in the experimental stage.

Large deposits of oil shale are known also in Sweden, Bulgaria, Bavaria, Italy and Switzerland, but they are

not being worked, although in most of these countries experimentation is now going on with a view to the exploitation of some of the richest of the deposits in the near future.

In Australia are large deposits of oil shale in New South Wales, Queensland and Tasmania. The most promising are in Tasmania, where spore deposits known as "tasmanite" furnish a material very rich in oil-making components. The estimated quantity of this material available is 12,000,000 tons.

The oil shale in New South Wales is in lenticular masses in coal measures of Permo-Carboniferous age. Some of the richest, known as "kerosene shale," is exported for gas-making. The balance is used locally.

Oil shales are known to exist also in New Zealand, Southern Africa, Argentine, Chile and Uruguay, but their value is unknown. Large deposits of high grade shale have also been reported in Manchuria, in Mongolia, in Arabia, in Syria and on the shores of the Dead Sea.

PRODUCTION

In 1925 the quantity of oil shale known to have been produced in the world was as follows:

TABLE XXVIII.—OIL SHALE PRODUCED IN 1925, IN METRIC TONS

Scotland	2,902,960	Italy	2,987
Estonia	233,631	Australia	2,253
United States	21,200	Bavaria	530

Other amounts were produced in France, Russia, Spain, and Sweden, but the quantities have not been reported.

Very little shale-oil has been produced in the United States except in an experimental way. In 1927 about 270,000 gallons were made from 5,000 tons of shale in experimental plants in California and Colorado, or at the rate of 50 gallons per ton of shale.

CHAPTER VII

COAL[1]

Coal is a mass of carbonaceous matter containing more or less fixed carbon. The evidence is so strong that it is of vegetable origin that time will be gained by assuming it at the beginning and proving it later.

VARIETIES

The classes of coal usually recognized are peat, brown lignite, black lignite or sub-bituminous coal, bituminous coal, semi-bituminous coal, semi-anthracite, anthracite and graphite. Cannel, carbonite, or natural coke and possibly anthraxolite[2] are special varieties a little out of the series.

Peat bogs consist of layers of living plants, dead partially carbonized plants, and a dense brownish black, more or less jelly-like mass without vegetable structure. The composition of the three layers is as follows:

	C	H	O	N
Sphagnum.....	49.88	6.54	42.42	1.16
Brown Peat.....	56.43	5.32	38.25	....
Black Peat.....	59.7	....	33.04	1.56

Lignite, or brown coal, is a partially carbonized wood. It is jointed and slabby.

Jet is a black lustrous variety from a coniferous wood that still shows the woody texture.

[1] The importance of coal and petroleum to modern civilization and their influence upon future national development and international relations are well described in W. T. Thom, *Petroleum and Coal, the Keys to the Future.* Pp. xviii and 223. Princeton, N. J., 1929.

[2] Anthraxolite is coal-like, but is probably a residue of some substance closely related to petroleum.

Black lignite is glossy-black and free from joints, i.e., is compact. When weathered it splits parallel to its bedding instead of into columnar forms like bituminous coal.

Bituminous coal is black and lustrous. It breaks with a cubical or conchoidal fracture, and shows woody structures under the microscope. Most bituminous coal is older than black lignite. Where the two occur together the lignite is commonly in horizontal layers and the bituminous coal is in contorted beds.

Coking and non-coking bituminous coals differ in their capacity for making a satisfactory coke that is strong enough to bear the burden of a considerable load. Whether a coal will coke or not depends primarily upon the quantity and character of its decomposed gelatinous constituents. According to Jeffrey[3] coals composed largely of spores are non-coking, whereas those composed mainly of wood are coking, provided the wood is not charred. The coking quality of a coal is usually determined by its hydrogen-oxygen ratio, estimated on a moisture-free basis, in relation to its fixed carbon percentage.[4]

When $\frac{H}{O} > 59$ the coal is usually coking, provided it contains no more than 79% of fixed carbon in pure coal. Coals containing over 79% of fixed carbon are coking only when the ratio between the volatile carbon and the fixed carbon (vc:c) is greater than one-tenth, though they may give good results in by-product ovens. Pishel[5] has described a convenient method of testing the coking-quality of a coal by crushing a small sample in an agate mortar and noting the way in which the powder adheres

[3] Jeffrey, E. C., "Coal in Relation to Coke," *Min. and Met.*, No. 1399–I, 1925.

[4] White, David, "The Effect of Oxygen in Coal," U. S. Geol. Sur., *Bull.* 382, pp. 48–60, 1909.

[5] Pishel, Max A., "A Practical Test for Coking Coals," *Econ. Geol.*, Vol. 3, p. 265, 1908.

to the surface of the mortar. If, after pulverizing the sample until its powder will pass a 100-mesh sieve and then emptying the mortar, a film of sooty material sticks to its surface the coal has coking qualities.

Semi-bituminous and semi-anthracite coals possess characters between those of bituminous and anthracite coal.

Anthracite coal is hard, brittle and lustrous and it possesses a conchoidal fracture. Its volatile constituents are small in amount.

Cannel coal is a compact non-coking bituminous coal with a dull luster and conchoidal fracture.[6] It contains large quantities of volatile components and is composed largely of spores.

Carbonite, or natural coke, is found at contacts of bituminous coals with igneous dikes.

Anthraxolite [7] is a coaly, lustrous, black substance occurring at a few places in veins in Pre-Cambrian rocks in Ontario, Canada, and elsewhere, and which, though very like a coal, is probably, nevertheless, a residue from petroleum.

Schungite [8] is a black, hard, metallic-looking substance with a specific gravity of 1.841, that is combustible with difficulty. It occurs as thin layers in a Pre-Cambrian slate, near Schunga, Govt. Olonetz, Russia. It closely resembles anthraxolite.

COMPOSITION

The composition of coals is usually expressed in terms of moisture, volatile matter, fixed carbon, ash and sulphur. This is known as the proximate analysis. The ultimate or elementary analysis is expressed in terms of ash, and the elements C, H, O, N, and S. The ultimate analysis is of

[6] Ashley, G. H., "Cannel Coal in the United States," U. S. Geol. Sur., *Bull.* 659, 1918.

[7] Coleman, A. P., "Anthraxolite or Anthracitic Carbon," *Sixth An. Rept.*, Ont. Bur. of Mines, pp. 159–161, 1897, and Rutherford, R. L., "Anthraxolite from the Northwest Territories of Canada," *Amer. Min.*, Vol. 13, pp. 516–518, 1928.

[8] Inostranzeff, A., *Neues Jahrb. F. Min.*, etc., 1880, Bd. I, p. 97 and 1886, Bd. I, p. 92.

very little use in estimating the value of a coal as fuel because it does not determine the manner in which the elements are combined, and consequently, therefore, does not indicate how much of each will burn. The proximate analysis states the proportions of combustible and non-combustible substances present, on the assumption that all the volatile matter (exclusive of moisture) is combustible. Parr, however, calls attention to the fact that some of the volatile matter is not combustible. He emphasizes the necessity of separating the "inert volatile" material from the combustible volatile hydrocarbon compounds. A few illustrations of the composition of well-known coals, expressed in terms of the proximate analyses, follows:

TABLE XXIX.—PROXIMATE ANALYSES OF TYPE COALS

	Ash	*Moisture*	*Volatile Matter*	*Fixed Carbon*	*Total Carbon*
Lignite, Lehigh, N. D.	11.42	32.64	29.19	26.75	39.53
Bituminous coal, Danville, Ill.	3.63	7.51	40.37	48.49	66.69
Bituminous coal, Carterville, Ill.	5.43	4.87	34.69	55.01	69.90
Coking coal, Wise Co., Va.	4.09	.924	35.97	58.44	....
Semi-bit. coal, Pocahontas, Va.	4.63	.65	18.80	75.92	85.91
Semi-anthr. coal, Blacksburg, Va.	18.80	.73	10.55	69.92	72.23
Anthracite, Scranton, Pa.	16.33	2.08	7.27	74.32	75.21

The relation existing between the ultimate constituents of wood and coals is well brought out by Clarke[9] who quotes a series of analyses to illustrate this relation.

[9] Clarke, F. W., "Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 757–773, 1924.

TABLE XXX.—ULTIMATE ANALYSES OF WOODS, PEAT, COALS, ETC.
(On ash, sulphur, and moisture-free basis)

	C	H	O	N
1	49.31	6.29	44.40	...
2	72.62	4.93	21.25	1.20
3	77.47	5.44	15.34	1.75
4	81.87	5.85	10.92	1.36
5	90.78	4.69	3.13	1.40
6	87.52	5.20	5.67	1.61
7	91.47	4.25	2.64	1.64
8	93.50	2.81	2.72	.97
9	96.69	.53	1.73	1.05
10	99.12	.44	....	.44
11	87.89	6.53	3.50	2.08

1. Average composition of 24 woods.
2. Brown lignite, Williston, N. D.
3. Black lignite, Red Lodge, Mont.
4. Bituminous coal, Staunton, Ill.
5. Bituminous coal, Ehrenfeld, Pa.
6. Average of 20 bituminous coals from Pa., Md., W. Va., and Va.
7. Semi-anthracite, Coal Hill, Ark.
8. Average of 16 analyses of anthracite coals.
9. Anthraxolite, Sudbury, Canada.
10. Schungite, Schunga, near Lake Onega, Russia.
11. Cannel coal, Tyneside, Scotland.

The average composition of the solid fuels as calculated by Clarke[10] are:

TABLE XXXI.—AVERAGE ULTIMATE COMPOSITION OF SOLID FUELS

	C	H	N	O
Wood	49.65	6.23	0.92	43.20
Peat	55.44	6.28	1.72	36.56
Lignite	72.95	5.24	1.31	20.50
Bituminous	84.24	5.55	1.52	8.69
Anthracite	93.50	2.81	.97	2.72

[10] Clarke, F. W., "Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, p. 773.

The proportions of the other constituents of fuels to 100 parts of carbon, calculated from figures in table above are:

Table XXXII.—Average Proportions of Constituents in Solid Fuels

	C	H	N	O
Wood	100	12.5	1.8	87.0
Peat	100	11.3	3.5	64.9
Lignite	100	7.2	1.8	28.1
Bituminous	100	6.6	1.8	10.3
Anthracite	100	3.0	1.3	2.9

Clarke's comments on these figures are:

"A steady decrease in hydrogen and oxygen thus becomes apparent. The data for nitrogen, however, are less conclusive, because of the uncertainty in the analyses of wood. If Hawes's average for the acrogen plants, 1.59% of nitrogen, be taken, then its ratio becomes 3.1, identical with the figure for peat, and a definite decrease follows. New analyses of wood, with references especially to its nitrogen content, are much to be desired.

A closer scrutiny of the foregoing table reveals still another fact, namely, that the proportional decrease in oxygen is greater than in the case of hydrogen. In cellulose, $C_6H_{10}O_5$, these two elements exist in exactly the proportions required to form water. In wood the hydrogen is slightly in excess of that ratio (1:8), and the excess steadily increases until in anthracite it is proportionally very large. In wood the ratio is nearly 1:7; in anthracite, roughly, 1:1."

With reference to the analysis of cannel coal (see Table XXX) he says (p. 770):

"The suggestive feature of the foregoing trio is in the proportion of nitrogen. The fossil plants contain very

little nitrogen; the cannels are abnormally high. The inference is that plant remains have contributed but a small part of the nitrogen contained in coal, and that the main supply has come from other sources. The most obvious source is animal matter, and this was probably the source of the nitrogen in cannel. Newberry[11] long ago pointed out that fish remains are abundant in cannel coal, and he argues that the beds were laid down under water. Vegetable matter formed a carbonaceous paste, in which the fish remains became embedded and which consolidated to produce cannel coal."

CLASSIFICATION

All classifications of coals are based on their analyses, the attempt being made to group together coals of similar qualities. Perhaps the most satisfactory is that of Parr[12] who distinguishes between volatile combustibles and volatile non-combustibles and uses the terms, vc = volatile carbon unassociated with hydrogen, C = total carbon, fc = fixed carbon, and inert volatile matter. The volatile carbon vc = C—fc. The inert volatile matter embraces the non-combustible volatile material, like water, oxygen and nitrogen. It is found by subtracting from 100% the sum of the total carbon, the hydrogen that is free to burn (i.e., that is not in water), the sulphur, the ash and the water. If reduced to the pure coal basis this remainder must be divided by 100, less the ash and water.

The value of a coal is determined mainly by the relative amounts of its combustible materials, viz.: volatile hydrocarbons and fixed carbon. The former favors kindling and the latter produces great heat. The fuel ratio is $\frac{\text{fixed carbon}}{\text{volatile hydrocarbons}}$. The presence of ash in a coal

[11] *Am. Jour. Sci.*, 2nd Ser., Vol. 23, 1854, p. 212.

[12] Parr, S. W., "Composition and Character of Illinois Coals," Ill. State Geol. Sur., *Bull.* 3, pp. 49–64, 1906.

PARR'S PROPOSED CLASSIFICATION OF COALS

Anthracite	Anthracite	$\frac{vc}{C} < 4\%$
	Semi-anthracite	$\frac{vc}{C} > 4\% < 8\%$
	Semi-bituminous	$\frac{vc}{C} > 10\% < 15\%$
Bituminous	A.	$\frac{vc}{C}$ from 20% to 32%, and inert volatile matter from 5% to 10%.
	B.	$\frac{vc}{C}$ from 20% to 27% and inert volatile matter from 10% to 16%.
	C.	$\frac{vc}{C}$ from 32% to 44%, and inert volatile matter from 5% to 10%.
	D.	$\frac{vc}{C}$ from 27% to 44%, and inert volatile matter from 10% to 16%.
Lignite	Black	$\frac{vc}{C} > 27\%$ and inert volatile matter from 16% to 20%.
	Brown	$\frac{vc}{C} > 27\%$ and inert volatile matter from 20% to 30%.

Parr's classification demands a knowledge of both the ultimate and proximate composition of the coals to be classified. Dowling[13] has suggested that a practical classification can be

[13] Dowling, D. B., "Classification of Coals by the Split Volatile Ratio," *Can. Min. Jour.*, Vol. 29, pp. 143–146, 1908.

based on determinations of fixed carbon, moisture and volatile combustibles. He uses the ratio

$$\frac{\text{fixed carbon} + \frac{1}{2}\text{ vol. combustible}}{\text{moisture} + \frac{1}{2}\text{ vol. combustible}}$$

which he calls the "split volatile ratio," and subdivides coal in accordance with this ratio: In anthracite the ratio is above 15; in semianthracite between 13 and 15; in bituminous coal between 3.5 and 6 and in lignite between 1 and 2.5.

decreases the quantity of combustible matter; it diminishes its heating value, and if the ash contains fusible materials, it favors clinkering. This is of such great importance that in coals sought for metallurgical work, the composition of the ash must be considered.

Sulphur is an objectionable impurity because when heated it produces sulphur dioxide, or other sulphur gases, that are corrosive, and because in smelting processes it enters the metal.

USE

Coal used in the production of gas may be high in ash and in moisture, since it is the quantity of gas that is generated that is of importance rather than the amount of heat produced. Lignites and low grade bituminous coals may be more economical for this purpose than higher grade coals because of their lower cost. For purposes other than gas production the most valuable coal is that which produces most heat for a given weight burned. Its value is determined by the number of heat units it contains, expressed in terms of British Thermal Units (B.T.U.) per lb. of coal as found by means of a calorimeter.[14] Other factors must be considered, however, in

[14] A British Thermal Unit is the number of pounds of water that one pound of fuel will raise 1° F. The B.T.U. value of pure carbon is 14,580, that of hydrogen is 62,000. Some coals of lower grade may have a greater heating value than anthracite because of their greater content of available hydrogen, i.e., of hydrogen which is free to enter into combination with oxygen, as distinct from that which is already combined with oxygen in water. The latter is in Parr's inert volatile matter; the former in volatile hydrocarbons.

estimating the value of a coal for consumption under specified conditions, the most important being its content of ash. The relative value of the different coals for heating purposes is dependent partly upon its B.T.U. and its cost. The U. S. government and the governments of many States and cities recognize this fact and therefore purchase their coal under specifications that have been carefully worked out, on the basis of the cost of 1,000,000 B.T.U.[15]

CARBON-RATIO

The ratio of fixed carbon to the sum of fixed carbon plus volatile matter is used as a measure of the amount of metamorphism suffered by the coal, on the assumption that its devolatilization is the result of thrust-pressure.[16] It has been found that the carbon-ratio increases slowly with depth of the coal bed, in regions of flat rocks, and increases markedly with increase in the amount of deformation the rocks have suffered. It has also been shown that it increases under unconformities, as should be expected, because the beds under an unconformity have suffered more alteration, because older, than those above it. Moulton,[17] for instance has calculated that the increase in carbon-ratio between the No. 5 and No. 1 coal in Fulton County, where there is no unconformity, is only 0.1, whereas where the two beds compared are separated by an unconformity, as are No. 6 and No. 5 in Gallatin County, No. 7 and No. 6 in Vermilion County, and No. 6 and No. 2 in Jackson County the increase in the ratios are respectively 1.3, 2.3 and 2.8. The carbon-ratio is used as a guide in the prospecting for oil as has already been noted. (See p. 97.)

[15] Pope, G. S., "The Purchase of Coal by the Government Under Specifications, with Analyses, Etc., for 1908–9," U. S. Geol. Sur., *Bull.* 428, 1910.

[16] White, David, "Some Relations in Origin Between Coal and Petroleum," Wash. Acad. Sci., *Jour.*, Vol. 5, pp. 189–212, 1915.

[17] Moulton, G. F., "Carbon Ratios and Petroleum in Illinois," State Geol. Sur. (Ill.). *Report of Investigations*, No. 4, 1925.

STRUCTURE

Lignites possess the structures of woods. Their origin is beyond question.

Other coals, except cannel, consist of alternating bright and dull layers (Fig. 66). The bright layers are fairly

Fig. 66.—Cross-section of coal.

homogeneous, and are of a jet-like texture. They vary in thickness from the fraction of an inch to several inches and in length from an inch or so to several feet. The smaller ones are distinct layers. The duller layers are usually finely laminated, the laminæ extending for short or long distances continuously. In some coals they are wavy and enclose lenses of the jet-like material, thin

scales of this and small fragments of bark, etc., spores and fragments of charcoal.[18]

When broken along the bedding the exposed surfaces show the impressions of leaves, wood fragments and debris of various kinds.

Thin sections of lignites show them to be composed mainly of fragments of carbonized coniferous wood that have been compressed and broken. In the interstices

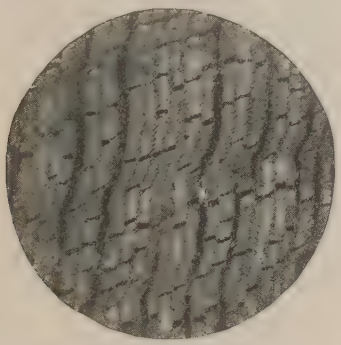


FIG. 67.—Microphotograph of lignite, showing well-preserved wood-structure, Lehigh, N. Dak. magnified. (*Courtesy of Prof. E. C. Jeffrey, Harvard Univ.*)

between the wood is a debris which consists of fragments of woody tissue, cuticles, resinous particles and spores, and its lamination is due to the presence of greater or less quantities of one or the other of these components (Fig. 67).

These are all embedded in what Thiessen[19] calls the attritus, or "fundamental matter," which consists of single cells or groups of cells, fragments of spores, resin particles,

[18] Jeffrey, E. C., *Coal and Civilization.* New York, 1925.

[19] Thiessen, Reinhardt, "Compilation and Composition of Bituminous Coals," *Jour. of Geol.*, Vol. 28, p. 185, 1920, and "Structure in Paleozoic Coals," U. S. Bur. of Mines, *Bull.* 117, 1920. (These articles are illustrated by numerous photographs of coal sections.) See also Jeffrey, E. C., *Coal and Civilization.* New York, 1925.

pollen grains and a cement of macerated cellulose, which was evidently once plastic.

Sections of sub-bituminous coals show the same features but everything is denser, more opaque and more compact

FIG. 68.—Microphotograph of bituminous coal, Donetz field, Russia. Layers of wood near top and bottom, cuticles, other tissues and a few spores. Highly magnified. (*Courtesy of Prof. E. C. Jeffrey, Harvard Univ.*)

FIG. 69.—Microphotograph of cannel coal, showing small pieces of wood and many flattened spores, etc., Blue Grass, Ky. Highly magnified. (*Courtesy of Prof. E. C. Jeffrey, Harvard Univ.*)

as though lignitic material had been subjected to physical or dynamic agencies and compressed (Fig. 68). The proportion of distinctly woody material is less than in the lignites, and of the debris greater, but this latter contains

more wood fragments. Moreover, there are present numerous fragments of charcoal ("Mother of Coal").

Cannel coal consists mainly of spores, with a debris of the same material with small quantities of resin, cuticles, etc. The binding material is like the fundamental substance of bituminous coal or is a very fine commingling of resin and spores (Fig. 69).

In the bituminous coals the jet-like laminæ are seen to be filled with resinous material. The cells are much com-

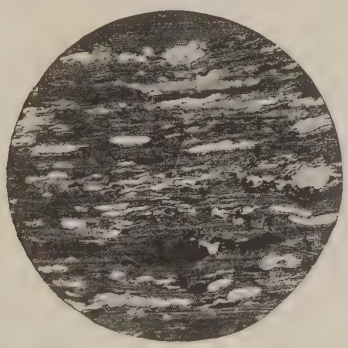


Fig. 70.—Microphotograph of bituminous coal showing much wood and few spores and cuticles. Catlin Co., Ill. (*Courtesy of Prof. E. C. Jeffrey, Harvard Univ.*)

pressed and often are completely collapsed. The dull layers are finely laminated debris substantially like the attritus in the lignites, but everything is much more compressed (Fig. 70). Thiessen declares that the bright layers consist of limbs and trunks of trees or parts of them which were not disintegrated previous to the formation of the coal. Its material retains the woody structure, though often somewhat distorted. The material of this bright coal, he calls "anthroxylon." The dull coal consists of numerous small layers or chips of anthroxylon embedded in a dull matrix—the attritus—which is composed of the waxy cuticles of leaves, spores and pollen exines, resinous

matter, small particles of resinous and woody matter partly carbonized, small rodlets or needles, that may be petrified gum or mucilage canals and small amounts of gums, pectins and cork. Scattered through both dull and bright layers are large and small fragments of charcoal.

Anthracite coal shows the same features as bituminous

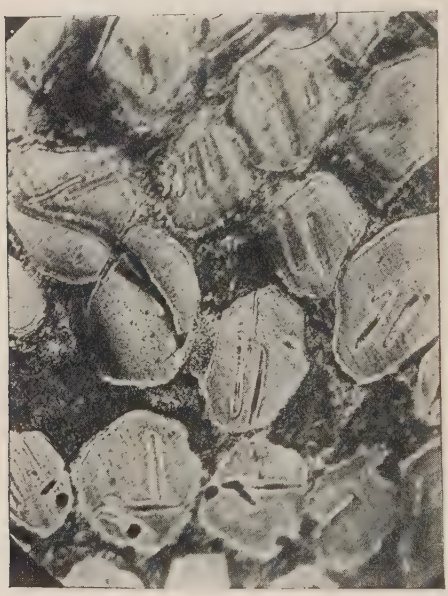


FIG. 71.—Microphotograph of etched surface of Pennsylvania anthracite, showing spore exines in dull layers. x 300. (*After Turner, Trans. Amer. Inst. Min. and Met. Eng., Feb. 1925.*)

coals, except for the greater abundance of structureless layers produced by the intense flattening of wood components. When the surfaces are etched spores of many kinds of plants become plainly visible [20] (Figs. 71 and 72).

The visible inorganic components of coal are calcium

[20] Turner, H. G., "Microscopical Structure of Anthracite," Amer. Inst. Min. and Met. Engrs., *Trans.*, Feb. 1925.

compounds, pyrite in cracks and as granules, and siliceous compounds in thin irregular deposits between the laminæ and in silicified wood fragments. The last named probably originated during the formation of the coal, the others after its formation. "But these visible ingredients

FIG. 72.—Oblique cross-section of etched surface of bright layer in Pennsylvania anthracite, showing woody structure. x 235. (*After Turner, Trans. Amer. Inst. Min. and Metal. Eng., Feb. 1925.*)

do not comprise all the mineral matter in coal; in fact, they comprise only the smaller part, because when a fragment of coal in which no minerals are visible is burned carefully, inorganic components are left uniformly from the whole fragment, the original form and texture of which is thus retained. The inorganic substances are seemingly in chemical union or close association with the organic components of the coal."[21]

[21] White, David, and Thiessen, Reinhardt, "The Origin of Coal," U. S. Bur. of Mines, *Bull.* 38, p. 266, 1913.

STRUCTURAL FEATURES OF COAL BEDS

Coal occurs in beds interstratified with rocks of Devonian or later age. At present no commercial beds are known in the United States with rocks older than Carboniferous and the most important beds are in the Pennsylvanian. All the coals older than Cretaceous are bituminous or anthracite except in Montana where a few are sub-bituminous. Cretaceous coals are bituminous or lignitic with the sub-bituminous varieties predominating in the earlier Cretaceous and lignite in the later Cretaceous. In a very few places where the conditions are exceptionable bituminous and anthracite are found in the same formation. The Tertiary coals are mainly lignitic, except in

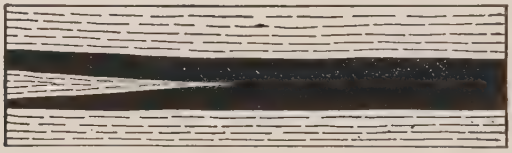


FIG. 73.—Diagram illustrating a split in a coal bed. (*After Emmons, General Economic Geology.*)

mountain districts where small quantities of anthracite and bituminous coals occur.

Normally several or more beds occur in any region, indicating that conditions favorable for the deposition of the materials from which coal was made recurred at intervals. In Pennsylvania 20 beds are known; in Alabama, 55 and in West Virginia over 100, but not all are workable.

The beds, or seams, vary widely in thickness, from a mere film to as much as 100 feet in rare instances. The Mammoth seam of Pennsylvania anthracite is 50 feet to 60 feet thick and in some places the great Pittsburgh seam of bituminous coal averages 75 feet thick. In some places a thick bed may break into several thinner ones separated

by sand and shale, from which it is inferred that while the accumulation was continuous in some portions of a basin it was interrupted in others (Fig. 73).

Indeed, rarely is any given bed uniformly thick over large areas. This irregularity in some cases is due to variations in the quantity of material deposited, and in others to local squeezing. These are the "pinchings" and

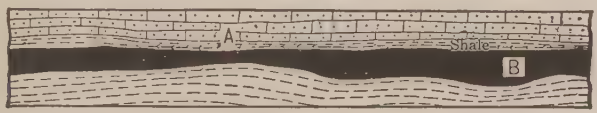


FIG. 74. –Cross-section of coal bed showing pinch (A) and swell (B). (*After Emmons, General Economic Geology.*)

"swellings" of the miners (Fig. 74). In regions of pronounced foldings the beds are usually found in separate synclinal basins, the intervening anticlines having been eroded.

Most coal beds are associated with shales, clays or sandstones, and in some places limestone, which usually lies

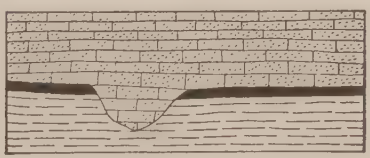


FIG. 75.—Diagram showing the absence of part of a coal bed as the result of erosion and the deposit of sediments on the eroded surface. (*After Emmons, General Economic Geology.*)

immediately over the coal, even though it may be of marine origin. The coal is often underlain by beds of fire clay or less refractory clays, in which are often found embedded stumps of trees and rootlets.

Irregularities.—Besides the splitting referred to many beds are faulted so that they disappear laterally, or they may wedge out or be replaced by shale or may disappear

as the result of erosional unconformities (Fig. 75). Splitting, however, is the most common irregularity. Beds of shale, usually flat lenses, are interspersed in the coal separating it into parts. When narrow, the shale is spoken of as a parting, and in some beds such a parting is so characteristic that it serves to identify the bed.[22]

Other irregularities are "squeezes" or "pinches," "swells," "rolls," "horsebacks," "clay veins," "stringers," etc., the nature of most of which is suggested by their names. The "horseback" is a projection of the floor or the roof into the coal bed. Its origin is explained in a number of ways, but not yet entirely satisfactorily.[23]

ORIGIN

There can be no question but that coal is derived from plant debris. All observers are agreed upon this: but the manner of accumulation of the material, the character of the organisms producing it, the initial processes of its decomposition and the nature of the forces bringing about the subsequent alterations that result in the varieties of coal are still matters of dispute.

Conditions of accumulation.—It is thought by some that nearly all coal beds are of *allochthonous* origin, i.e., that their material is not of local origin. Some coals are in thin wedges or lenses that are sharply outlined. They are not underlain by clays and show no penetration of roots into the underlying strata. These are regarded as accumulations of driftwood. Moreover, many coals consist mainly of spores which must have been deposited

[22] Savage, T. E., "Clay-seams Near Springfield, Illinois," *Econ. Geol.*, Vol. V, p. 178, 1910.

[23] Illustrations of some of these kinds of irregularities are given in "Coal Resources of District VII," by Fred H. Kay: Illinois Coal Min. Investigations, *Bull.* 11, pp. 167–169 and 196–199, 1915, and in E. S. Moore, *Coal, Its Properties, Analysis, Classification, Geology, Extraction, Uses and Distribution.* New York, pp. 215–237, 1922.

in open water. Cannel coal is of this type. Though nearly everyone concedes that this coal represents the settlings in open water, most geologists regard the accumulation as similar to that now occurring in northern woodland lakes where 20 feet to 40 feet of slime, composed mainly of spores blown in from the surrounding forests, covers their bottoms.

Most geologists see in the perfect preservation of many plant remains in the more common kinds of coals, in the presence of upright trunks, in the coal with their roots penetrating the underlying clay, which is nearly always present, and in the admixture of genuine charcoal with carbonized wood, evidence that the accumulation was *autochthonous*,[24] or made in place in swamps like the Great Dismal in Virginia and North Carolina and the Great Sumatra Swamp. Stevenson is convinced that the coal-producing material was deposited on old river plains that gradually sank, causing their valleys to be filled.

These accumulations were evidently near tide level since (1) marine beds are often intercalated in the coal measures and are sometimes found immediately over the coal without any unconformity between them, and (2) the different coal beds in a series are generally parallel through great thicknesses, indicating little if any tilting between successive beds. The coal plants, however, were fresh water species, so that during their growth the sea must have been denied ingress into the swamp. In most cases the coal-forming plants must have grown in coastal or lacustrine swamps developed in regions of slight submergence of a broadly extended peneplain. Where the rate of submergence was slow the beds were able to maintain themselves and accumulate to great thicknesses, since perhaps

[24] Stevenson, J. J., "Formation of Coal Beds," Amer. Phil. Soc., *Proc.*, Vol. 50, 1911, Vol. 51, 1912, and Vol. 52, 1913, especially pp. 550–553 in Vol. 51 and pp. 120–154 in Vol. 52.

20 feet of debris is represented by 1 foot of coal (50 feet of coal = 1,000 feet of debris).[25] When the rate became more rapid the plants were killed and sandstones, limestones, etc., were deposited over them until the area had again been built to water-level and plants could again establish themselves. White[26] declares that "Coal that may be attributed to the mere accumulation of drift vegetation is very restricted in area and variable in thickness and much of it is too high in ash to be of value" (p. 66). "At many points small areas of open water, temporary in duration, occurring in the midst of swamps, were marked by concentrations of spores, resin, waxes, etc., forming cannel layers or lenses, the more destructible matter being lost by decomposition" (p. 63). Irregular variations in water level account for the lamination of the coal. "Such periods of water reduction appear generally to have been attended by concentration of the hydrocarbon solutes resulting from the putrefaction in the form of paste which now constitutes the binder of the coal" (p. 64).

Processes of decomposition.—Assuming that all the coal plants were accumulated under shallow water it is plain that they must have suffered a different series of changes to cause them to yield such different products as lignite, bituminous coal and anthracite. It is now generally conceded that the changes were wrought in two stages:

a. The putrefaction stage, resulting from biochemical causes.

b. The metamorphic stage, resulting from dynamo-chemical causes.

Ries[27] summarizes White's conclusions with reference

[25] Ashley's estimate is that 2,100 years were required to produce 7 feet of the Pittsburgh coal from peat, or 300 years per foot of coal. "The Maximum Rate of Deposition of Coal," *Econ. Geol.*, Vol. 2, pp. 34–47, 1907.

[26] White, David and Thiessen, Reinhardt, "The Origin of Coal," U. S. Bur. of Mines, *Bull.* 38, pp. 52–90, 1913.

[27] Ries, H., *Economic Geology*, 5th Ed., New York, 1925, pp. 14–15.

to the first stage in these words: "When dead vegetable matter accumulates under water, it does not remain unchanged, but undergoes a deoxygenation and dehydrogenation process, which is accomplished by fermentation or maceration in which minute plants (bacteria) and also animals take part. As a result of this the plant tissues break down to a greater or less degree, depending on the stage of decay. The change may advance no further than to convert the mass into woody or fibrous peat, or it may go far enough to obliterate most of the plant structures, giving a somewhat jelly-like black peat, which changes into the so-called amorphous coal. It is highly probable that the process of decay had not advanced to the same stage in all peats prior to their burial under sediment." Concerning the second stage White[28] writes: "On termination of the biochemical action we have, so far as known, only an unconsolidated, non-dehydrated peat occluding methane and other fluid decomposition products that have not yet made their escape. If the process has gone on to an advanced state it is a black or more 'mature' peat, in which most of the plant matter has decayed, or possibly an 'amorphous' peat; if it is less advanced, the peat, containing much wood or other matter largely undecomposed, is brown and less 'mature'; and if the vegetable refuse falls into more nearly 'aseptic' water the decay is relatively little and the peat is lighter brown and fibrous or distinctly xyloid" (p. 92).

Thus it may happen that some peat may be more completely deoxygenated than some lignite so that it may possess a higher calorific value than the latter. Moreover, in much high-grade coal the vegetation is less decomposed than in much mature peat. In general, each rank of coal "presents in itself essentially the same range, from the

[28] White, David, and Thiessen, Reinhardt, "The Origin of Coal," U. S. Bur. of Mines, *Bull.* 38, 1913.

'amorphous' type in which the vegetable debris is mostly reduced to minute, often microscopic, vestiges * * * to the xyloid type, in which the wood in the form of mineral charcoal or jet-like fragments, many of large size, is abundant and readily seen with the naked eye" [29] (p. 94).

Consequently the different kinds of coal must be due in large part to causes that have operated since bacterial action ceased. During the putrefaction stage the vegetal mass was compacted and gases were expelled, the liquid putrefaction products that form the cementing paste, or binder, of the coal were partly hardened, and the fuel mass, much reduced in volume, assumed the character of a stratified mineral sediment. Marsh gas (CH_4), CO_2, H_2S and H_2O were expelled by the mere weight of overlying sediments and certain changes were effected in the other products of the biochemical processes, but what these changes were we do not know since we do not know the nature of the organic compounds in any coal. The most evident change was the devolatilization of the coal. Its ultimate stage results in the almost complete expulsion of oxygen and hydrogen, a loss of part of the nitrogen and of a smaller relative portion of carbon. The final stage is graphite, which is approached through anthracite, bituminous and lower grades of coal. The reduction of the volatile combustible matter of the fuel was accompanied by slight loss of its two heat-producing elements, hydrogen and carbon, with relatively greater conservation of carbon. The loss of oxygen (originally 40% of the vegetation) was much greater so that the net result is an increase in the value of the coal as fuel. The efficiency of the coal was increased in passing from peat to

[29] Jeffrey denies the importance of the biochemical agencies in the production of coal, and ascribes the change of vegetable tissue into coaly matter to hydrolysis, i.e., the direct action of water on woody material which has been submerged and protected from the air. See his *Coal and Civilization*, 1925.

semi-bituminous coal, until the volatile combustibles were reduced to 18% of the total combustible, after which its value fell off considerably, with additional losses of volatile material. Hydrogen was lost slowly up to this point, but in passing from the bituminous to the anthracitic stage both hydrogen and oxygen were lost rapidly.

With deformational changes in the attitude of the coal-bearing series, pressures are increased by lateral movements and thrusts, wood tissues are further broken down, more gases are pressed out, new chemical processes are engendered through increases in temperature, diminution in water content, etc., and the changes that are initiated by load-pressure are carried to completion with much more rapidity than would otherwise have been the case. Further, all the plant structures are compressed until in some cases they are no longer recognizable. "But," says White, "all the cells remaining at the end of the microbian action of the biochemical process are present, and, up to the last stage of the metamorphism are optically (and possibly chemically) differentiated, though the substances are changed chemically and reduced in volume" (p. 95). On the other hand, he says that he has frequently observed semi-bituminous coal and anthracite of Tertiary or Cretaceous ages that were totally indistinguishable, either chemically or by physical characters, from the corresponding coal of Paleozoic age, except by paleobotanical recognition of the geologic age of the enclosed plant fragments.

The work of the dynamochemical process is therefore, in short, the "devolatilization" of the coal.

All geologists attribute to dynamic forces in part the change from vegetable matter to anthracite coal, but they do not all agree that thrust-pressure is the principal agency through which most of the high-grade coal has been made. The objections to this theory are all briefly

discussed in the bulletin [30] by White and Thiessen. It might be remarked in passing that Campbell [31] would ascribe the changes produced in coals not to folding alone, since he believes he has evidence that coal beds in equally deformed regions are of different grades. He asserts, however, that the character of the folding, as well as the amount of folding, is of great importance in determining the nature of the coal. There must be opportunity for the gases to escape if devolatilization is to be brought about. If the rocks associated with the coal are cracked so that the gases may escape, a higher grade of coal is produced than if the case were otherwise.

Other explanations of the causes of variations in the quality of coal have been proposed, but White [32] and a few others have emphasized [33] so strongly the effects of thrust-pressure, exhibited in folding, faults, cleavage, schistosity, etc., as the cause of the devolatilization of coal, that most geologists are now convinced that it is the only cause that will explain the origin of anthracite, although Stevenson [34] believes that anthracite has not been developed through bituminous coal but that its volatile constituents were partly removed by longer exposures of the vegetable matter to oxidation before burial.

Graphitic coal.—Graphitic coal represents apparently one of the last stages in the production of coal from vegetable matter. In the United States it occurs in highly metamorphosed Carboniferous rocks near Providence,

[30] U. S. Bur. of Mines, *Bull.* 38, pp. 96–130.

[31] Campbell, M. R., "Hypothesis to Account for the Transformation of Vegetable Matter into the Different Varieties of Coal," *Econ. Geol.*, Vol. 1, p. 26, 1905, and discussions of Lane, *Ibid.*, p. 498, and Smith, *Ibid.*, pp. 581–3.

[32] *Econ. Geol.*, Vol. 3, p. 311, 1908, and Vol. 4, pp. 279–280, 1909, and U. S. Bur. of Mines, *Bull.* 38, p. 105.

[33] Moore, E. S., *Coal, Its Properties*, etc. New York, 1922, pp. 123–177.

[34] Stevenson, J. J., "Formation of Coal Beds," Amer. Phil. Soc., *Proc.* Vol. 52, p. 31, 1913.

R. I., where it constitutes a 30-foot bed of sandy shaly material, which may have been originally a very dirty bed of vegetable debris from which most of the volatile material and some of the carbon has been lost by extreme metamorphism, thus increasing the relative proportion of ash in the resulting product. The material can be used as a fuel only in specially constructed furnaces. It cannot compete with other coals at Providence except at half the price of these. It is proposed to utilize it at the mines for generating electricity which can be delivered at Providence at nominal cost for transportation.[35]

Cannel coal.—Cannel coal has recently become of great interest because of its large content of volatile hydrocarbons and the possibility of its being a satisfactory source of oil, artificial gas, tar, ammonia and benzol. It is a massive, non-coking, tough, clean, black coal of fine, even, compact grain, with a dull luster, and a conchoidal fracture. It has a low fuel ratio, and a high percentage of hydrocarbons. It ignites easily, burns with a long, yellow flame and falls into powder when burned out. It has a black to brown greasy streak and a moderate ash content. It is composed mainly of decomposed spores, pollen, and other vegetal and some animal debris (sapropel), with which may be admixed mud, and woody or peaty material. It grades into bituminous coal by increase in the woody and peaty component.

Chemically it differs from bituminous coal in its low fixed carbon and high volatile carbon contents. Analyses of a cannel and a bituminous coal from the same bench at Chenoa, Bell County, Kentucky, illustrate this difference.

	Fixed Carbon	*Volatile Matter*	*Fuel Ratio*
Cannel	40.4	51.6	.77
Bituminous	62.3	32.6	1 90

[35] Ashley, G. H., "Rhode Island Coal," U. S. Geol. Sur., *Bull.* 615, 1915.

Cannel coal differs from ordinary bituminous coal also in the fact that it occurs only in small basins that may represent old channels or lagoons. The locations of all those known to exist in the United States are described by Ashley.[36] The largest deposits known are in Eocene rocks in Webb County, Texas, near Laredo, and in eastern Kentucky. The total production of true cannel in the United States in 1913 was about 180,000 tons, of which Kentucky contributed one-half.

COAL FIELDS OF THE UNITED STATES

The principal coal fields of the United States (Fig. 76) with their areas are:

TABLE XXXIII.—PRINCIPAL COAL FIELDS IN THE UNITED STATES

	Square Miles
The Appalachian	69,755
Atlantic Coast Triassic	210
Eastern Interior	47,000
Northern Interior	11,000
Western Interior	74,900
Gulf Coast Lignite	2,100
Rocky Mountain	126,022
Pacific Coast Field	1,000
Alaska	1,210

APPALACHIAN FIELD.—The Appalachian field, which is the most important, contains nearly nine-tenths of the high-grade coal of the country. It has been the foundation of the development of the blast furnaces, the iron and steel mills and many of the manufacturing enterprises of the Eastern States. All of its coal is in the Pennsylvanian series, which consists of a great thickness of overlapping lenses of conglomerate, sandstone, limestone, shale, fire-clay and coal. The formations thin

[36] Ashley, G. H., "Cannel Coal in the United States," U. S. Geol. Sur., *Bull.* 659, 1918.

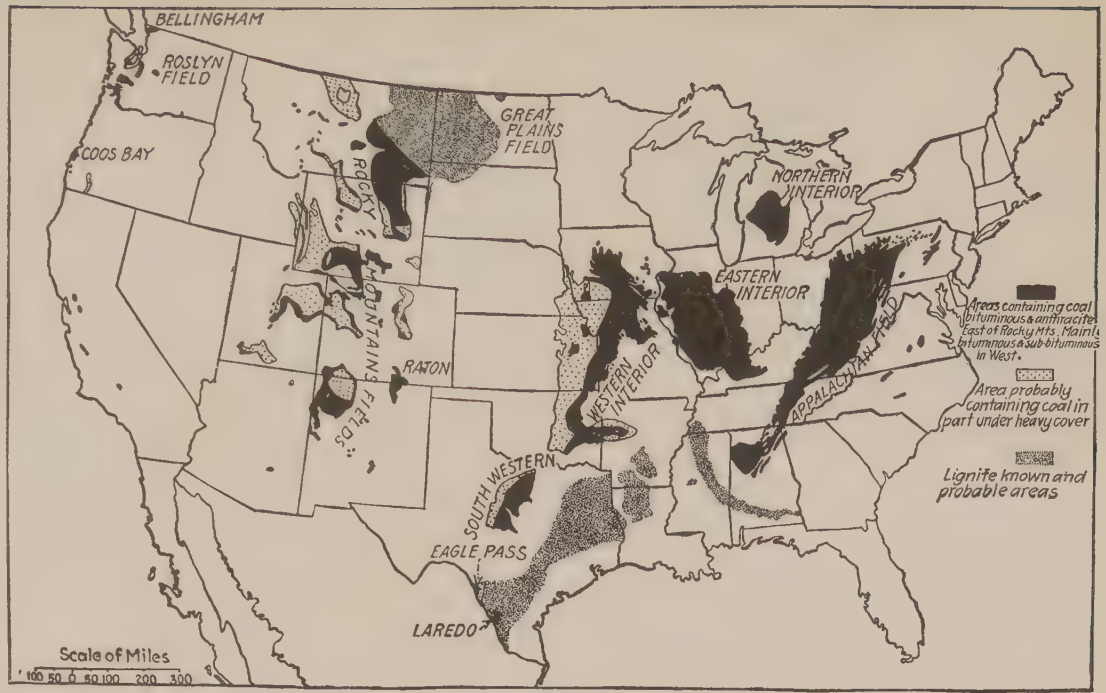


FIG. 76.—Map showing distribution of coal fields in the United States. (*After U. S. Geol. Survey.*)

toward the west and show a decrease in number and thickness of the coals.

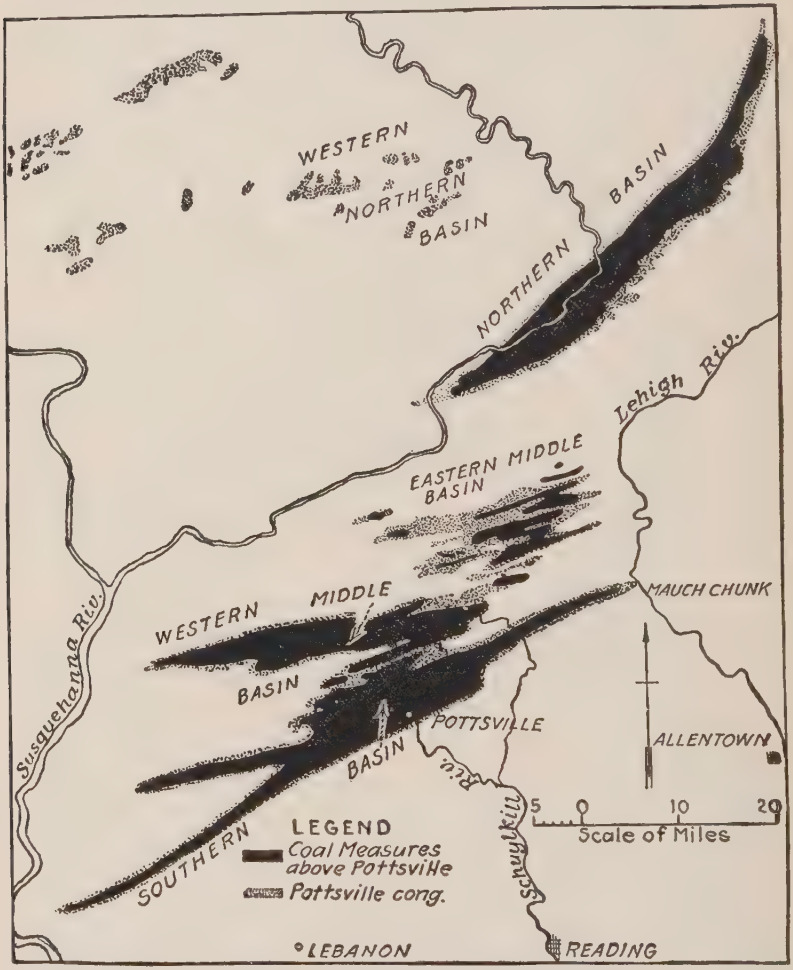


FIG. 77.—Map of anthracite region in Pennsylvania. The stippling shows position of the Pottsville formation, which lies immediately beneath the coal-bearing beds. (*Adapted by Emmons in General Economic Geology, after Smith, Stoek and others.*)

The field is divisible into two parts—one producing anthracite and the other bituminous coal.

Anthracite region.—The anthracite region is a group of crescentic areas in the northeast portion of Pennsylvania completely isolated from the greater part of the Appalachian district which extends southwesterly along the west side of the Allegheny Mountains (Fig. 77) from Pennsylvania to Alabama. The anthracite district has an area of only 1,000 square miles, but it furnishes nearly all the anthracite produced in the country, about 78,500,000 long tons in 1924. The coal occurs in separated narrow basins that are fairly steeply folded synclines (Fig. 78). The coal when mined is mixed with hard slate, or "bone," that must be picked out by hand or by machine in "breakers." The refuse, known as "culm," contains an abundance of fine coal. This is now being washed and put on the market.

Bituminous region.—The bituminous region occupies nearly 69,000 square miles of which 12,000 are in Pennsylvania. In the north the coal is in synclinal basins separated from one another by eroded anticlines. The synclines are not as sharp as in the anthracite region, and the coal is semi-bituminous and semi-anthracitic. Farther south the coal is in flat folds that are almost horizontal. Here it is bituminous and much of it is coking. While most of the coal beds are of more limited extent, the celebrated Pittsburgh seam is 7 feet or more thick over 2,100 square miles and contains 9,641,000,000 short tons of coal. In this area are also the famous New River and Pocahontas coals in Virginia and West Virginia (Fig. 79). In Virginia some of the coals are associated with Mississippian beds. In general the rocks along the eastern margin of the field are more closely folded than those farther west, and likewise the coal associated with them is of higher grade in the eastern part of the field than in its western part. Their percentage of fixed carbon decreases from east to west and the volatile matter increases in the same

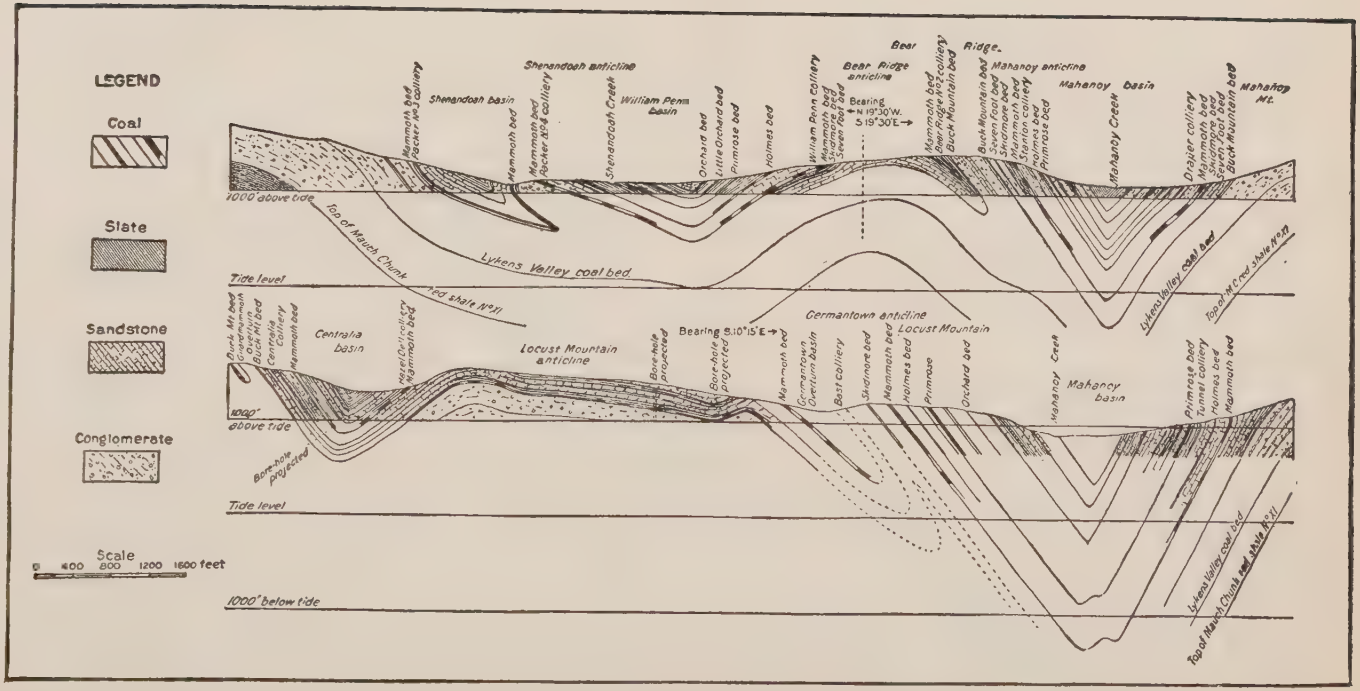


FIG. 78.—Sections across anthracite basins in Pennsylvania. (*After Smith, Stoek and others, in Emmons: General Economic Geology.*)

direction. White[37] has shown that this variation is characteristic for the entire field and has drawn contours of equal percentages of fixed carbon, showing the change. All the semi-bituminous coals are on the eastern side of the field, but even along this side they are irregularly disposed, due, according to White, to variation in the pressure exerted in the coal-bearing rocks while they were being folded.

Triassic field.—The Triassic area of Virginia and North Carolina is no longer of importance, though it was first worked in 1700. It includes several steep sided

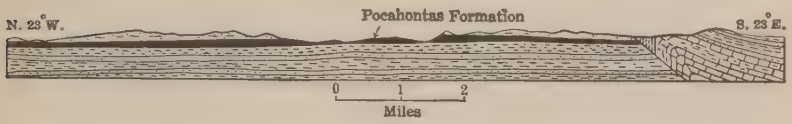


Fig. 79.—Section across the Pocahontas coal field 3 miles west of Pocahontas, Va. (*After Campbell and White, U. S. Geol. Sur., Folio 26.*)

basins of Triassic rocks folded down into the crystalline rocks of the Piedmont plateau. The coal is cut by dikes and sheets of igneous rocks that have changed it in places to coke.[38]

Eastern Interior field.—The Eastern Interior field is mainly in Illinois, southwestern Indiana and western Kentucky. The coals, which lie in gently folded Pennsylvanian rocks, vary in number in different portions of the field and are thus difficult to correlate. The lower seams in Illinois are better than the upper ones, and their quality improves from north to south. The coal is bituminous but is in general non-coking by the usual

[37] White, David, "Some Relations in Origin Between Coal and Petroleum," Wash. Acad. Sci., *Jour.*, Vol. 5, pp. 180–212, 1915.

[38] Shaler, N. S., and Woodworth, S. B., "Geology of the Richmond Basin, Virginia," U. S. Geol. Sur., *19th An. Rept.*, Pt. 2, pp. 385–515, 1899; and Woodworth, J. B., "The Atlantic Coast Triassic Coalfield," U. S. Geol. Sur., *22nd An. Rept.*, Pt. 3, pp. 25–53, 1902.

processes. In the southern part of the State, however, there is a small area in which the coal is suitable for coking. The cannel coal of Kentucky is in this field.

Northern Interior field.—The Northern Interior field is limited to southern Michigan where the coal is in a basin of Carboniferous rocks. It is entirely bituminous, and some of it cokes.

Western Interior field.—The Western Interior field extends with minor interruptions from northern Iowa to central Texas. Except in western Arkansas and eastern Oklahoma, the beds are nearly horizontal. The coals are Pennsylvanian in age. They are bituminous, and non-

Fig. 80.—Cross section of coal field near Coalgate, Okla. Horizontal and vertical scales the same. (*After Taff, U. S. Geol. Sur. 22nd An. Rep., Pt. 3, 1902.*)

coking. In Oklahoma and Arkansas near the Ouachita Mountains where the beds are sharply folded, the coals range from bituminous to semi-anthracite (Fig. 80). Though non-coking they are the best coals found west of West Virginia.

Gulf Coast field.—The southern part of the Western Interior field is generally considered a distinct field, which, including a comparatively small area in southwestern Tennessee, northeastern Mississippi and southern Alabama is designated the Gulf Province. The coal is mainly lignite contained in Eocene beds. The field is not at present of commercial importance, because coal of much better quality is nearby in central Texas, Oklahoma, and Arkansas. The lignite beds cover portions of southeastern Texas, southern Arkansas, northwestern Louisiana, the southwestern corner of Tennessee, and occupy a strip

of country extending from northwestern Mississippi to southeastern Alabama.

Rocky Mountain field.—The Rocky Mountain field comprises a number of small districts occupying a general area that extends from Canada to New Mexico. The coals range from Lower Cretaceous to Eocene. Most of the beds in the north have been but slightly disturbed and the coal is mainly lignite, but farther south they have been folded and cut by igneous intrusions and the coals associated with them are bituminous or anthracitic. The latter is the case especially at Crested Butte in Colorado and in the Cerrillos field in New Mexico, where igneous intrusions are abundant. The principal bituminous beds are in Colorado, Wyoming and Utah and the western part of Montana where they are involved in the mountain folds. The northern portion of this field is sometimes separated in discussions from the remainder and is called the Northern Great Plains Province. It occupies portions of the States of Montana, North Dakota, South Dakota and Wyoming and a small part of Colorado. The rocks are generally flat or but slightly folded Cretaceous beds and the coal is lignitic or sub-bituminous. Where they are more closely folded, as on the west flanks of the Black Hills, the grade of the coal is higher and in some places is of bituminous rank. At Cambria, Wyoming, it has been made into coke. Bituminous coal of coking grade also occurs at Great Falls and Lewistown, Montana, and in Colorado north of Denver.

The Raton Mesa region in southern Colorado and northern New Mexico is also often included in this province although it is situated east of the Front Range. The coal is in steep folds and is cut by stocks and dikes of igneous rocks, and consequently is of high grade. Much of it makes excellent coke which is supplied to many of the smelters in the Rocky Mountain Province.

Pacific Coast fields.—The Pacific Coast coals are all Tertiary. They occur in scattered basins of small areal extent, mainly near the coast in Washington and Oregon. The Washington areas are the most important, but the Coos Bay area [39] in Oregon is a steady producer. In these areas, the best coal is sub-bituminous but elsewhere it is lignitic. The quality of the coal in the Pacific Coast field varies with the dynamic disturbance of the rocks in which it occurs,[40] and hence there may be a variation in a single field. Some of the coal is coking.[41]

Alaskan fields.—Coal is known to exist in Alaska at a number of localities (Fig. 81), but up to the present time it has been exploited on a very small scale, only 711,986 short tons having been produced to the end of 1924. At present the production supplies about five-ninths of Alaska's consumption. Most of the coal in the country is lignite in Eocene beds, but a little anthracite occurs in the Tertiary (Eocene or Miocene) on Bering River and bituminous and sub-bituminous coals in the Eocene of Matanuska Valley,[42] in the (Fig. 81) Yukon basin and on Cook Inlet. In the Cretaceous of the Alaska Peninsula, lignite occurs in Tertiary beds within the basin of Nenana River [43] and in the Yukon and Colville basins, in the Jurassic in Matanuska Valley and near Cape Lisburne and in the Carboniferous south of Cape Lisburne and the

[39] Diller, J. S., "The Coos Bay Coal Field, Oregon," U. S. Geol. Sur., *19th An. Rept.*, Pt. 3, pp. 309–376, 1897–98.

[40] Smith, G. O., "The Coal Fields of the Pacific Coast," U. S. Geol. Sur., *22nd An. Rept.*, Pt. 3, pp. 473–513, 1902.

[41] For a comprehensive discussion of the different coal fields in the United States see Campbell and others, "The Coal Fields of the United States," U. S. Geol. Sur., *Prof. Paper* 100, 1917.

[42] Martin, G. C., and Katz, F. J., "Geology and Coal Fields of the Lower Matanuska Valley, Alaska," U. S. Geol. Sur., *Bull.* 500, 1912.

Capps, S. R., "Geology of the Upper Matanuska Valley, Alaska, With a Section on the Igneous Rocks by J. B. Mertie, Jr.," U. S. Geol. Sur., *Bull.* 791, 1927.

[43] Martin, G. C., "The Nenana Coal Field, Alaska," U. S. Geol. Sur., *Bull.* 664, 1919.

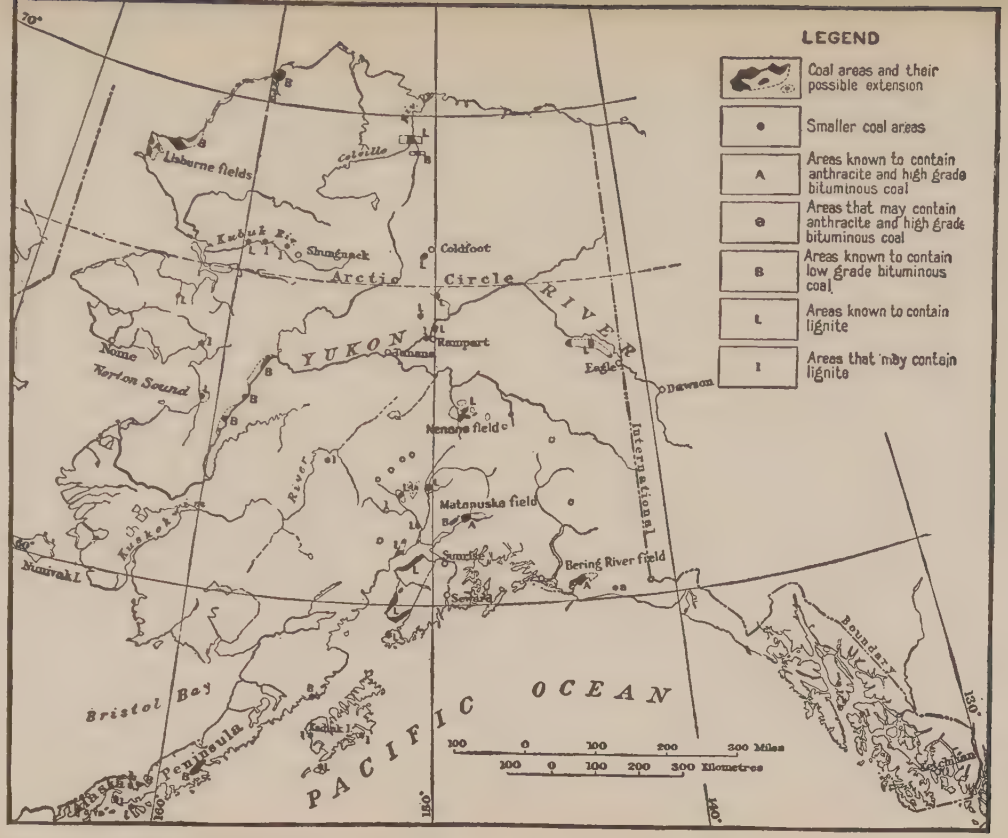


FIG. 81.—Map of Alaska showing positions of principal coal fields. (*After Brooks and others, U. S. Geol. Sur., Bull. 442, Pl. I.*)

Yukon River. Most of the coal beds are faulted, crushed and are difficult to mine. The reserves in the Nenana basin are estimated to be 9,000,000,000 tons. Most of the coal comes from the Matanuska field because it is accessible to the Alaska Railroad, but equally good coal is known to exist in the Valley of Bering River. The best coal is in the upper part of the valley, but this is not yet being mined on a large scale. Most of the coal that is shipped is a sub-bituminous grade like that on Vancouver Island. The high-grade coals are said by Brooks[44] to be from 25% to 30% more valuable than the sub-bituminous and lignitic grades now being mined, but because of the friable character of the coal, its gaseous condition and its irregular occurrence mining costs are very great.[45]

PRODUCTION

The total production of coal in the United States since shipments began in 1807 had aggregated 16,234,098,138 net tons to the end of 1924. Of this quantity 12,817,-456,378 tons were of bituminous and 3,416,641,760 tons were anthracite.

The production of the individual fields in 1922 is shown in the following table. In this year the total output of anthracite was 54,683,022 long tons and of bituminous coal 422,268,099 tons. The corresponding figures for 1926 were 84,437,452 tons and 573,366,985 tons (Table XXXIV).

Some of the tonnage listed under bituminous was lignite. The value of the aggregate tonnage was $1,183,412,000.

The maximum production of anthracite coal was in 1917, when 99,611,811 tons were mined, and of bituminous and lignite in 1918, when the tonnage was 579,385,820.

[44] Brooks, A. H., "Mineral Resources of Alaska," U. S. Geol. Sur., *Bull.* 739, p. 16, 1923.

[45] For map showing positions of known coal areas in Alaska see, "Mineral Resources of Alaska," U. S. Geol. Sur., *Bull.* 662, 714 A.

TABLE XXXIV.—PRODUCTION OF COAL FROM THE VARIOUS FIELDS IN THE UNITED STATES IN 1926

(In tons of 2,000 lbs.)

Anthracite		84,437,452
Bituminous:		
Appalachian	415,885,347	
Northern Interior	686,707	
Eastern Interior	108,016,952	
Western Interior	16,522,646	
Rocky Mountain	27,138,989	
Pacific	2,536,568	
Northern Great Plains (lignite)	1,370,244	
Alaska	104,300	
Gulf Coast (lignite)	920,664	
		573,366,985*
TOTAL		657,804,437*

* Totals include small amounts from scattered States.

In addition to the coal in 1922, there were produced 60,680 short tons of peat, valued at $397,729 and in 1926 about 61,936 tons, valued at $364,413, but none of it was used as fuel.

IMPORTS AND EXPORTS

In 1922 the imports were 5,059,999 tons of bituminous coal and 233,528 tons of anthracite, most of it from Canada and the United Kingdom. The quantity imported in 1922 was, however, above the normal importation since there was a shortage of domestic coal, due to a great strike. Normally about 1,300,000 tons are received, nearly all of it bituminous coal from Alberta and Vancouver Island for use in the Pacific States, Montana and Idaho.

In 1927 the imports were only 486,000 short tons of bituminous coal and 814,000 tons of anthracite, the increased imports of anthracite being due to the strike in the anthracite region in the early part of the year. In this year most of the bituminous coal came from Canada and most of the anthracite from England.

Exports vary widely from year to year depending largely upon industrial conditions in outside countries. Most of it goes to Canada, Italy, Brazil, Argentina, Cuba and France.

TABLE XXXV.—EXPORTS OF COAL FROM UNITED STATES DURING THE YEARS 1922–1926 IN NET TONS

Bituminous

To	1922	1924	1926
North America	11,807,864	14,153,639	15,591,313
Canada	10,836,347	12,654,869	13,633,513
Mexico	101,983	91,507	128,630
Cuba	519,521	598,921	615,721
South America	343,606	1,251,548	2,729,526
Europe	170,915	1,519,780	15,805,243
Asia	21	17,381	29,893
Africa	90,679	146,269	1,106,536
Oceania	0	11,730	9,426
TOTAL	12,413,085	17,100,347	35,271,937
	Anthracite		
To Canada	2,572,450	3,927,999	3,941,718
Other countries	77,007	89,786	87,965
TOTAL	2,649,457	4,017,785	4,029,683

PRINCIPAL COAL FIELDS OUTSIDE THE UNITED STATES

NORTH AMERICA—*Canada.*—In Canada coking bituminous coals occur in Nova Scotia and New Brunswick in slightly folded rocks that range from Lower Carboniferous to Permian. In Western Canada coals similar to those farther south in the States are fairly abundant. In the Great Plains region where the beds are horizontal the coals are lignitic or sub-bituminous, but, farther west in the mountain areas they are bituminous or anthracite. These are all Cretaceous or Tertiary. In British Columbia the coal measures are chiefly Lower Cretaceous and the coals are generally bituminous, but in a few places because of close folding and the action of igneous intrusions they

have become anthracitic. Scattered deposits of Tertiary lignitic coals are also known in this area, and in some places where affected by igneous intrusions they are bituminous. On Vancouver Island are Upper Cretaceous, more or less folded, beds that contain sub-bituminous and bituminous coal. The reserve in this area has been estimated at 1,000,000,000 tons.[46]

Mexico.—In Mexico the most important fields are of Cretaceous bituminous coals along the Texas border.

Europe.—Europe contains extensive deposits of Carboniferous bituminous coals in Western Germany, Belgium, Northern France, Russia, England and Scotland, and Carboniferous anthracite in Wales and Russia. Tertiary sub-bituminous and lignitic coals are mined in Southern Russia, Austria, Germany and France. The relative resources of France and Germany in the commodity became a matter for serious consideration at the close of the World War, and an attempt was made in the Versailles treaty in the interest of permanent peace to equalize the conditions, so that Germany should no longer control the monopoly of coal and iron production in Europe. Some of the studies made for the use of the Allied representatives have since been published,[47] as has also a discussion [48] of the relations of the coal in the disputed fields to the iron and steel industries of Europe. As a result of the disposition made of the territory by the Versailles agreement, France now controls about 48% of the European iron ore reserves, while

[46] Dowling, D. B., "Coal Fields and Coal Resources of Canada," Geol. Sur. of Canada. *Mem. Geol. Series* No. 55, 1915, and "Coal Fields of British Columbia," *Idem.* No. 57, 1915.

[47] Crooks, E. G., "Notes on the Coal Industry of Northeastern France, Belgium, The Saar and Westphalia," *Econ. Geol.*, Vol. 15, pp. 277–311, 1920.

[48] Brooks, A. H., and La Croix, F., "The Iron and Associated Industries of Lorraine, The Saar District, Luxemburg, and Belgium," U. S. Geol. Sur., *Bull.* 703, 1920.

Germany, on the other hand, still owns in the Westphalian fields the largest reserve of coking coal in continental Europe. Neither country is in a position to dominate the iron-making industry, as did Germany before the War.

Asia.—Asia contains extensive areas of Permo-Carboniferous coals in China and India, among which are all grades from lignite to anthracite, and Tertiary bituminous coals in Japan and northeastern Siberia.

Australia, South America and Africa.—Australia contains Carboniferous and Tertiary coals, South America, Tertiary coals along the Pacific and Gulf coasts and Africa, Carboniferous to Jurassic coals in its southern part. The quantity of coal in Australia, South America and Africa is not large as compared with that in North America and Asia.

WORLD PRODUCTION

The production of coal in the world during 1927 was not as great as would have been the normal production had there been no World War. With an increase in the industrial activity of Europe it is probable that its proportion of the world's production in the near future will be larger.

Table XXXVI.—The World Production of Coal in 1926

(In metric tons of 2,204.6 lbs.)

North America	559,208,000
South America	2,100,000
Europe	790,924,000
Asia	90,378,000
Africa	13,971,000
Oceania	17,612,000
Total (approximate)	1,470,000,000

The most important producing countries in 1927 were:

United States	542,365,652
Germany	304,103,268
United Kingdom	255,265,125
France	52,847,000
Poland	38,162,550
Japan	33,500,000
Czechoslovakia	33,636,937
Belgium	27,573,550
China	24,255,000
Russia, in Europe	27,448,262
Russia, in Asia	4,502,963
British India	22,436,757
Canada	12,341,000
Australia	15,218,845
Saar	13,595,824
Union of South Africa	12,580,314

* In 1925.

No other country produced over 10,000,000 tons.

RESERVES

World.—Because of the great importance of coal in the production of heat and power for the manufacturing and metallurgical industries, attempts have been made to estimate the quantity still remaining in the rocks, in order to obtain some idea as to how long it will last. It is realized that the rate of consumption in the future may be quite different from that in the past, because of the possible development of other sources of power, and because of discoveries which will result in a greater efficiency in the utilization of all grades of coal, particularly of those of low grade.

The best estimate of the coal reserves of the world is that made by the committee of The International Geological Congress,[49] with the aid of geologists in the coal-

[49] *Coal Resources of the World*, 12th International Geological Congress, 1913.

producing countries. This result is only approximate, as our knowledge of many of the coal fields in Asia and Africa is very scanty.

TABLE XXXVII.—RESERVES OF COAL IN THE WORLD IN 1912

(In millions of metric tons) (1 metric ton = 1.1023 short tons) (Including all seams more than 1 foot thick and less than 4,000 feet deep and seams over 2 feet thick between 4,000 and 5,000 feet deep)

	Anthracite	*Bituminous*	*Lignite and Subbituminous*	*Total*
United States	19,684	1,955,521	1,863,452	3,838,657
Canada and Newfoundland	2,158	284,161	948,450	1,234,769
Mexico and Central America		1	4	5
South America	700	31,397	.....	32,097
Europe	54,346	693,162	36,682	784,190
Asia	407,637	760,098	111,851	1,279,586
Oceania	659	133,481	36,270	170,410
Africa	11,662	45,123	1,054	57,839
TOTAL	496,846	3,903,444	2,997,763	7,397,553

Of the total the United States is credited with more than 50%.

At the present rate of production, the estimated life of all the coal fields in the world is about 4,500 years.

UNITED STATES.—The reserves in the United States, according to Campbell,[50] as of 1914, together with the total production of the different fields to this date are shown in the table on following page.

Although only about four-tenths of 1% of the coal has been removed from the ground or wasted,[51] the greater part of that mined is of the best grades. Con-

[50] Campbell, M. R., "The Coal Fields of the United States: General Introduction," U. S. Geol. Sur., *Prof. Paper* 100, pp. 1–33, 1917.

[51] It is estimated that the waste in some districts is equal to about 50% of the coal mined.

TABLE XXXVIII.—RESERVES OF COAL IN THE UNITED STATES AT THE END OF 1914, ACCORDING TO DISTRICTS

(In short tons)

	Total Production	*Estimated Supply Within Depth of 3,000 Feet*
Appalachian fields:		
Anthracite region	2,537,500,000	17,194,000,000
Bituminous region	5,238,700,000	543,039,000,000
Triassic fields	477,125	799,000,000
Interior fields:		
Northern and Eastern	1,439,863,000	319,830,000,000
Western and Southwestern	575,038,000	208,044,000,000
Gulf fields	10,510,000	23,074,000,000
Northern Great Plains fields	236,937,000	1,294,180,000,000
Rocky Mountain fields	204,698,000	1,067,609,000,000
Pacific Coast fields	114,929,000	64,785,000,000
TOTAL	10,357,706,400	3,538,554,000,000

sequently the exhaustion of the best supply will antedate that of the total supply by many centuries, since the great bulk of the coal in this country is low-rank bituminous, lignite, and sub-bituminous named in the order of their abundance. The high rank coals are relatively scarce.

COKE

Although coke is a manufactured product, nevertheless it should at least be mentioned briefly in connection with any discussion of coal, because of its importance in the iron industry.

Coke is produced in the United States mainly in ovens constructed primarily for making it, but it is obtained also in the refining of petroleum, in the refining of coal tar and in the manufacture of coal gas. The coke that is made as a by-product in the petroleum and gas industries is not strong enough for most metallurgical purposes. A little

petroleum coke is employed in making electrodes, but most of it and nearly all of that made in gas-works is used for heat production or in the manufacture of water-gas. Coal-tar coke, or pitch coke, which is at present made only in small quantity, is used in foundries.

In 1926 the production of coke-oven coke amounted to 56,865,537 short tons, which was valued at $307,773,402. In the following year the production was only about 51,000,000 tons, the decrease being due to the diminished activity of blast furnaces. Most of the decrease was in bee-hive coke.

TABLE XXXIX.—STATISTICS RELATING TO THE COKE INDUSTRY IN THE UNITED STATES DURING 1926

	Bee-hive	*By-product*	*Total*
Number of ovens	52,558	11,716	64,274
Coal used, net tons	19,224,500	63,646,610	82,871,110
Coal used, value	$38,541,691	$247,170,284	$285,711,975
Coal used, value per ton	$2.00	$3.88	
Coke produced, net tons	12,488,951	44,376,586	56,865,537
Coke produced, value at ovens	$57,024,869	$250,748,533	$307,773,402
By-products sold:			
Gas, M. cubic feet		397,914,088	
Tar, gallons		277,248,522	
Ammonium sulphate, lbs.		1,152,141,717	
Ammonia liquor (NH_3 content), lbs.		53,448,034	
Crude light oil, benzol, etc., gallons		135,793,595	
Naphthalene, lbs.		7,723,223	
Value of by-products sold:			
Gas (surplus)		$64,686,800	
Tar		14,103,760	
Ammonia sulphate		24,658,031	
Ammonia liquor		3,470,172	
Crude light oil, benzol, etc.		27,304,976	
Naphthalene		97,310	
Other products		148,720	
			$134,469,769

Only the coke-oven coke is of interest at present. Two kinds of ovens are employed in the industry—the bee-hive

oven, which is cheaper to install, but which wastes all the gaseous and liquid products of combustion, and the by-product oven, which is expensive but which is so constructed as to save the combustion products. In 1926, there were in the United States 52,558 bee-hive ovens and 11,716 by-product ovens, and in addition 978 by-product ovens were under construction. Statistics relating to the coke industry are collected annually.[52]

Imports and Exports.—Coke is such a bulky and cheap product that very little enters foreign trade. In 1926 there were exported, mainly to Canada, about 987,000 tons, valued at $6,979,896, and there were imported about 284,550 tons, valued at $2,174,350. Nearly all the imports came from England, Canada, Germany and the Netherlands.

The world's production of coke in this year was about 107,000,000 metric tons, of which amount the United States contributed 51,600,000 tons, Germany 27,550,000 tons and Great Britain 4,800,000 tons, besides 11,785,000 tons of gas-house coke.

The most important use of coke is in the metallurgical industries, consequently the distribution of coke ovens not only indicates the localities of coking coals, but it also marks the favorable positions for furnaces and smelters. By consulting such a map, it will be seen that the coke ovens in the United States are crowded together in the Appalachian field and are scattered elsewhere.[53] Those that are scattered are to be found either around small isolated areas of coking coal or at industrial centers that are easily reached from coking coal districts either by water or by short rail hauls. The points of consumption

[52] Tryon, F. G., and Bennit, H. L., "Coke and By-products in 1927," U. S. Geol. Sur., *Min. Res., 1927*, Pt. II, pp. 595–686, 1929.

[53] See Lesher, C. E., "Map of the United States Showing Distribution of Coke Ovens (in 1916)," U. S. Geol. Sur., *Min. Res., 1915*, Pt. II, Pl. IV, 1916.

of coke are more widely spread than the points of its production, although most of it is consumed where made.[54]

For some years attempts have been made to manufacture coke from the coals of the Eastern Interior field, since if a process can be discovered that will produce a satisfactory product from these coals, the same process, or a similar one, may be used to coke other coals that are now regarded as non-coking. It is known that a coke sufficiently good for domestic use can be made by mixing Illinois coal with low volatile coking coal from foreign sources,[55] but it is hoped to make a coke from Illinois coal alone. In the southern portion of the State are two small areas[56] in which the coal is comparatively low in sulphur; less than 1.25%. These two fields will furnish a suitable quality of coal for coke making, when a process is developed for coking it to a satisfactory product.

Coke breeze is the screenings from coke ovens that are too fine for metallurgical or household use. Most of it is used as a boiler fuel by its producers and by gas plants. In 1926 it is reported that 4,301,795 tons were saved. Its value was estimated at about $9,880,000.

PEAT

In Europe peat has been employed extensively as a fuel for local use in those countries in which coal and wood are scarce. In America its principal uses are as a fertilizer and as an ingredient in stock food. It is produced by the slow decay of plant remains that have accumulated under water, where they are protected from the action of the oxygen of the air. The decay is accomplished by the agency of organisms (see page 201) which break down

[54] Tryon, F. G., U. S. Geol. Sur., *Min. Res., 1922*, Pt. II, Pl. VI.

[55] Ovitz, J. K., "Coking of Illinois Coals," U. S. Bur. of Mines, *Bull.* 138, 1917.

[56] Cady, G. H., "Low-Sulphur Coal in Illinois," Illinois State Geol. Sur., *Bull.* 38, p. 432, 1922.

the vegetable tissues with the extraction of oxygen and the liberation of carbon. If not very much altered the resulting peat is light-colored, and is fibrous if produced from mosses. If much altered it may be dark and compact. When compressed by the weight of overlying material it is structureless and in many places may be contaminated by sand or mud. Most peat is formed from sedges and moss-like plants, but it may be formed from herbaceous vegetation of any kind. It accumulates in lakes, in fresh-water marshes, in flat moist depressions (bogs), particularly in regions of heavy rainfall, and in salt marshes, which are poorly drained flat areas that are periodically inundated by sea-water.[57] The salt-marsh peat, according to Davis,[58] consists, as a rule, of material of fresh-water origin beneath a relatively thin layer of salt-water peat, indicating that the deposit was made on a slowly sinking coast. Some deposits are composed entirely of salt-marsh plants. The peat made from these is usually too much mixed with salt to be of much commercial value.

When intended for use[59] as a fuel the peat is cut from the bog and is simply air-dried, or it is compressed into blocks with or without a binder. Varieties of peat that are comparatively rich in nitrogen are dried and used for filler in artificial fertilizers. Fibrous varieties are employed for packing and after being saturated with nutritious substances are fed to live-stock. Powdered peat is also used to some extent as a deodorizer and as a disinfecting agent.

In 1926 about 62,000 short tons were produced in the

[57] Bastin, E. S. and Davis, C. A., "Peat Deposits of Maine," U. S. Geol. Sur., *Bull.* 376, 1909.

[58] Davis, C. A., "Origin and Formation of Peat," U. S. Bur. of Mines, *Bull.* 38, pp. 165–186, 1913.

[59] Davis, C. A., "The Uses of Peat for Fuel and Other Purposes," U. S. Bur. of Mines, *Bull.* 16, 1911.

United States. Its value was about $364,500. In addition, 16,670 tons of peat moss, with an estimated value of $175,250, were imported.

LIQUID COAL

Within recent years it has been suggested that coal may be used to produce a substitute for petroleum when the supply of this substance is exhausted. It is known that part of the loss may be made good by the manufacture of oil from oil shales, and it is believed that another part may be made good by the transformation of coal into oil. If, as suggested by White, coal is the result of processes similar to those resulting in the production of oil, there would seem to be promise that under proper treatment it might be made to yield a product closely similar to petroleum.[60]

Low-temperature carbonization.—When a ton of some coals is heated at temperatures below 600° C. it may be made to yield a moderate volume of gas of high heating power, from 1,000 to 1,400 lbs. of semi-coke and from 20 to 40 gallons of a thin tar. The semi-coke when briqueted with a suitable binder serves as an excellent smokeless fuel. The tar is different from ordinary coal-tar in that it can be cracked (see p. 136), to yield about 22% of anti-knock motor fuel. By several of the many processes experimentally employed in low-temperature carbonization low-grade coals and screenings of all grades may be transformed into valuable products. At present none of these processes are operated on a commercial scale, but when the price of gasoline increases or the cost of processing the coal decreases, coal may be expected to furnish a product that will take its place.[61]

[60] Nash, A. W., "Possible Auxiliary Sources of Liquid Fuels," Inst. Petrol. Tech. (London), *Jour.*, Vol. 13, pp. 688–712, 1927.

[61] Stuart, Murray, *Low Temperature Carbonization Explained.* London, 1929.

Berginization.—The process of Bergius for the conversion of coal into oil is believed to be most promising. Pulverized coal made into a paste with oil, and heated at temperatures of about 450° to 480° C. in an atmosphere of hydrogen under a pressure of 150 to 200 atmospheres, and in the presence of iron oxide or some other catalyst, is largely changed to oil and tar from which motor fuel, Diesel oils, lubricants and heavy fuel oil are recovered. Bergius apparently considers that the iron oxide is not essential to the success of the process, but other workers believe it acts as a catalyst, aiding hydrogenation. British bituminous coals yield under berginization from 20 to 60% of thin tar, 15 to 20% of gas and 10% of solid uncarbonized and partly carbonized coal. Bergius reports that a metric ton (1,000 kilograms) of bituminous German coal yielded 235 kilograms of gas, 5 kilograms of ammonia, 240 kilograms of coke, and 525 kilograms of oil (thin tar) from which were made 150 kilograms of motor spirit, 200 kilograms of Diesel oil, 60 kilograms of lubricating oil and 80 kilograms of fuel oil.

The berginization process is being applied experimentally not only to coal, but also to the solid and semi-solid residues of petroleum in the hope that it may result in the commercial production of gasoline and other motor fuels from materials that are at present of little value.[62]

[62] For a summary outline of the progress made in the production of liquid fuels from oil, see *Oil and Gas Jour.*, Dec. 29, 1927, pp. 140 and 180.

CHAPTER VIII

SALINES

Under this heading are included certain definite chemical compounds that occur as minerals, or in solutions from which they can be separated on a commercial scale. Some of those that occur as minerals have been thrown out of solutions either by evaporation, by chemical reactions, or through the agency of organisms. Others have been formed by chemical reaction upon solid substances. Others occur in the tissues of organisms. A large portion of those in solutions exist in the water of the seas, the ocean, lakes, rivers, and springs, from which they may be separated by artificial means, mainly by evaporation. Some of these may be produced more economically from insoluble mineral compounds than by evaporation of their solutions, and have, therefore, driven the natural products from the market. For instance, borax was formerly obtained by the evaporation of the water of certain lakes; now it is made from the minerals colemanite and kernite. Further, some salines are obtained as by-products in certain manufacturing processes, and, since they are identical with the natural substances and are used for the same purposes, the value of the natural compounds is largely dependent on the prices at which the manufactured compounds can be placed on the market.

Among the most important saline substances are common salt (NaCl), sodium sulphate, sodium carbonate, calcium sulphate, calcium chloride, sodium nitrate, potassium nitrate, sylvite, other potassium salts, borax and certain bromides and iodides. Some of the compounds

enter the trade in their original forms, but others are sold as sources from which more valuable marketable products are obtained. The latter is true of the bromides and the iodides which enter trade mainly as bromine and iodine.

Most of the salines that occur as minerals have been precipitated from solutions by natural processes. Their nature depends upon the composition of the solutions from which they were separated, upon the processes that caused their separation, and upon the conditions under which it took place.

DEPOSITS FROM THE OCEAN AND SEAS

The principal substances of value deposited from ocean water are common salt, the fertilizer salts—kieserite, kainite, carnallite and sylvite—and magnesium bromide. They are deposited in layers. All the characteristic constituents of the great salt deposits at Stassfurt, in Germany, are accounted for on the supposition that they were precipitated from sea water that was evaporated at about 25° C. (See p. 292.) The order of the layers in the Stassfurt beds is:—rock salt, kieserite zone (kieserite, kainite and halite), carnallite zone (kieserite, carnallite and halite) and bischofite zone.

Iodine and potassium are taken from sea water by certain plants and built into their tissues, from the ashes of which they may be obtained by extraction with water.

CHARACTERISTIC DEPOSITS FROM LAKES

Differences between ocean and lake waters.—Since the water of the ocean and the seas represents the drainage from the entire surface of the land, its composition is nearly uniform throughout, and consequently, the deposits from it are everywhere similar, except for variations caused by differences in the conditions that produced precipitation.

Lakes, however, are fed from local sources. Their water can contain only such ingredients as are obtained from the rocks within their drainage areas, from springs, or from the air. The water of lakes with outlets is fresh, because there is no accumulation of the dissolved materials in their basins. Lakes in basins belonging to interior drainage systems become charged with salts, because they possess no outlets through which material coming to them can be discharged. The water is lost by evaporation, consequently the solutions gradually become more and more concentrated. Some of the solutions contain the same constituents that are present in ocean water, but in different proportions. Others lack some of the substances found in ocean water, or contain them only in minute quantities, and in addition contain large amounts of other substances that are absent from ocean water or which are present in it in such small quantities as to be negligible as sources of commercial products.

The important salt components of lake waters are alkaline carbonates, nitrates, sulphates and borates, as well as those that are present in large quantities in ocean water.

The most favorable sites for interior drainage are in arid regions. The lakes of such regions are often replete with salts of various kinds, and these salts vary in character as the nature of the rocks surrounding the lakes varies. (See Fig. 82.) Among the most typical of these lakes are salt lakes, bitter lakes, alkali lakes and borax lakes.

Salt lakes.—In the salt lakes the principal salt is NaCl. Some salt lakes obtain their salt by the solution of salt beds, others receive it from buried brines. Many become salt through the action of ordinary weathering processes. The waters supplying such lakes drain rocks whose original decomposition products are mainly carbonates with smaller proportions of chlorides and sulphates. The car-

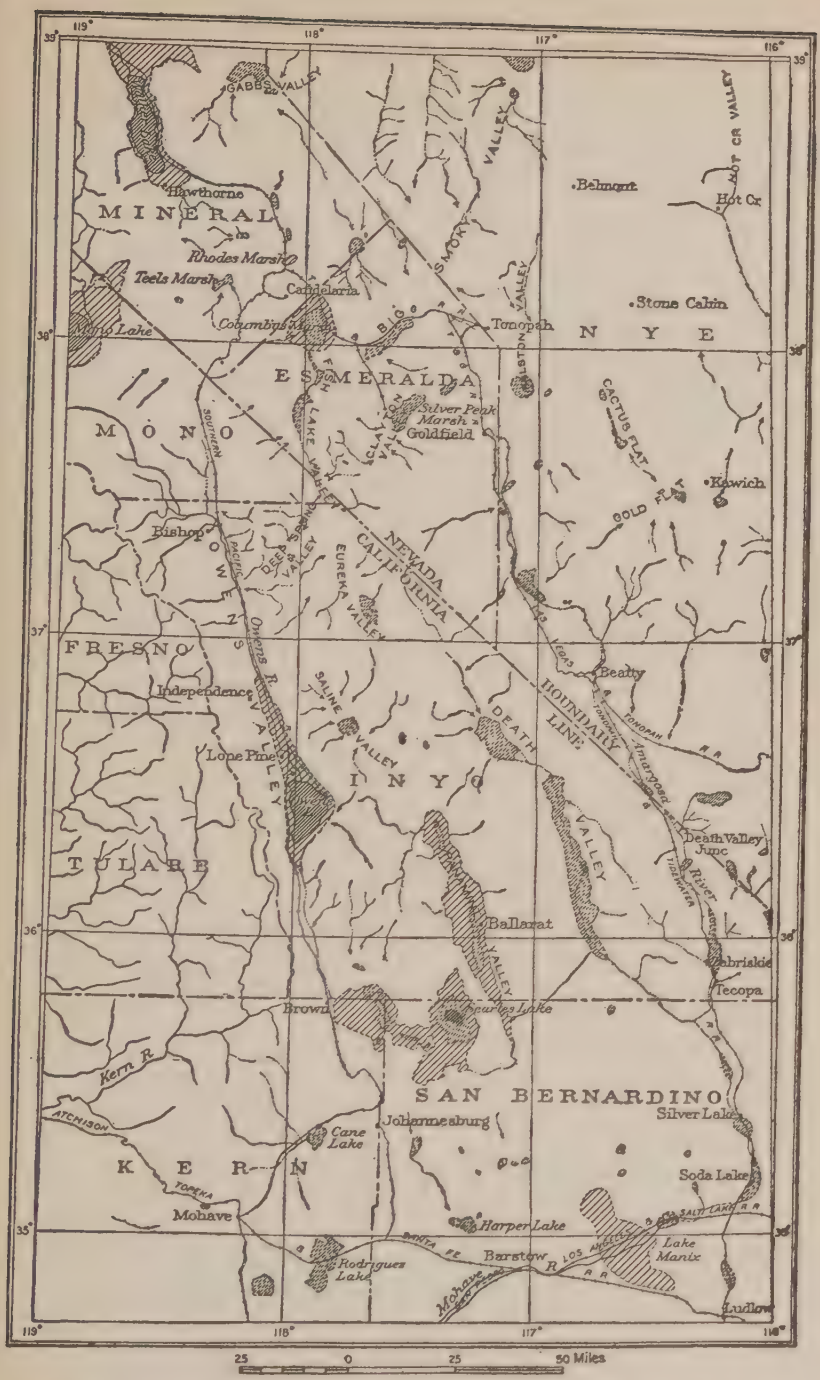


FIG. 82.—Map showing locations of principal saline lakes and playas in S. E. California and S. W. Nevada. *(After Gale, U. S. Geol. Sur., Bull. 580.)*

bonates precipitate as the streams dwindle and the chlorides and sulphates become proportionately increased. Then gypsum is thrown down, leaving mainly chlorides in the solution.

Thus, Humboldt River feeds Humboldt Lake. The analysis in line I represents the solid matter in the river water, and that in line II the solid matter in the water of Humboldt Lake into which the river flows. In line III is the composition of the salts in Pyramid Lake, which represents a concentration more pronounced than Humboldt Lake.

	Cl	SO_4	CO_3	Na	K	Ca	MgO	SiO_2	Salinity (Parts per 1000)
I.....	2.19	13.92	39.55	13.63	2.92	14.28	3.62	9.51	0.361
II.....	31.82	3.27	21.57	29.97	6.54	1.35	1.88	3.53	0.929
III.....	41.04	5.25	14.28	33.84	2.11	.25	2.28	.95	3.486

Salt lakes of this type rarely deposit rock salt, except as efflorescences around their margins.

In regions of slight rainfall, however, many lakes which are only a few inches deep during the rainy season may become nearly dry when the rains cease, producing "salt marshes" or "playas" in the mud of which all the salts of the lakes may occur, some of them as efflorescences, others as thin beds and others in the concentrated brine between the solid mud constituents. In many of the playas deposits of common salt may be made, but this is so intimately intermingled with other salts that it has no commercial value.

The playas, however, are important sources of some of the rarer salts.

Bitter lakes.—Bitter lakes are those in which sulphates predominate. In some the sulphate is obtained by the

solution of buried beds of sulphates, but in others it is produced by the decomposition of rocks containing sulphides.

Red Lake in Wyoming has a salinity of 93.10 parts per thousand, and its water contains:

Cl	SO_4	B_2O_7	Na	Ca	Mg
3.06	64.57	.57	29.89	.59	1.32

In Wyoming there are about a hundred depressions containing concentrated solutions of alkaline sulphates or deposits of sulphates, mainly in the form of Glauber's salt as efflorescences around their borders.[1] Their deposits usually consist of alternating layers of salts, sand and mud, and the mud, if above water, is covered with efflorescences of white alkali (sodium sulphate).

The most noted bitter lake in the United States is Soda Lake in southwestern California (Fig. 83). This is a playa through most of the year. Its area is about 3,000 acres. It is a broad, flat plain of white crystalline salt ranging from a thin sheet to a layer a few inches thick. The salt consists of a mixture of 81.86% Na_2SO_4 and 8.97% NaCl, with a small quantity of other components. It is estimated by Gale[2] that the deposit contains over 1,000,000 short tons of the sulphate. Deposits from other lakes are known to occur at numerous places in the far western States but they have not yet been exploited, though some of them are now being explored.

Russia contains numerous lakes in which the content of sulphates is very great. Most of these are in the Yeniseisk region in Siberia. Lake Altai is the most famous. Its salinity is 108.78 parts per thousand, of which 78.90 parts are contributed by Na_2SO_4 and 25.77 parts by NaCl.

[1] Knight, W. C., and Slosson, E. E., "Alkali Lakes and Deposits," Wyo. Exp. Sta., *Bull.* No. 49, pp. 84–88, 1901.

[2] Gale, H. S., "Notes on the Quaternary Lakes of the Great Basin," U. S. Geol. Sur., *Bull.* 540–N, pp. 428–433, 1914.

Glauber's salt separates from its water in winter and is collected for use in glass factories.

The waters of Soda Lake in California and of Gill Lakes in Wyoming are being worked and the Glauber's salt is

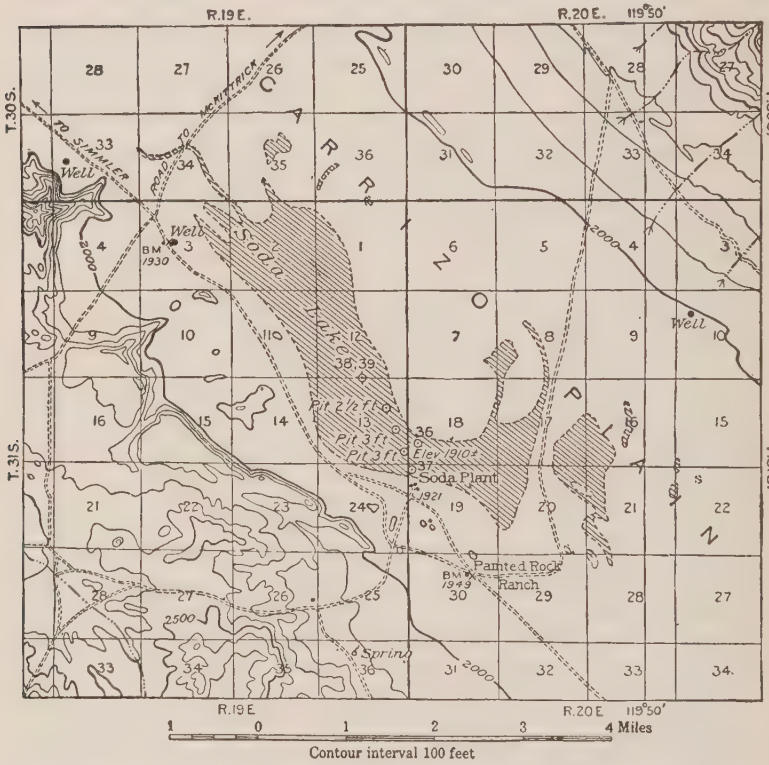


Fig. 83.—Map of Soda Lake, San Luis Obispo Co., California. (*After Gale, U. S. Geol. Sur., Bull. 540.*)

desiccated by solar heat to anhydrous "salt cake," which is in great demand for use in the manufacture of wood pulp in the sulphite process. About 90,000 tons are consumed annually in Canada and the United States.

Alkali lakes.—Alkali lakes contain predominantly carbonates of the alkalies. They are common in the Great

Basin in Nevada and California. (See Fig. 82.) While it is probable that in most lakes the Na_2CO_3 present has been derived directly by decomposition of volcanic rocks, in some lakes its presence is due to the action of algæ on Na_2SO_4, in others to reaction between $CaH_2(CO_3)_2$ and Na_2SO_4 or NaCl, and possibly in others to the action of zeolites on $CaCO_3$, as for instance:

$$Na_2O.Al_2O_3.2SiO_2 + CaCO_3 = CaO.Al_2O_3.2SiO_2 + Na_2CO_3.$$

The K_2CO_3 present in some lakes is the indirect product of the action of organisms.

Sodium carbonate deposits as an efflorescence, known as "black alkali," in the mud around the lakes and as layers in the lake bottoms. The purified salt is known in the trade as soda ash, natron, sodium bicarbonate and trona.

The Soda Lakes in Nevada, Mono Lake and Owens Lake in California and Goodenough Lake in British Columbia are the best known alkali lakes in North America and the Natron Lakes in Egypt are the most famous abroad.

The Soda Lakes of Nevada are fed almost entirely by springs percolating through volcanic rocks containing zeolites. The water of the lakes contains 428,000 tons of Na_2CO_3, 400,000 tons of Na_2SO_4 and about 1,200,000 tons of NaCl, but its deposits consist of hydrated salts that include about 45% of Na_2CO_3, about 34.6% of $NaHCO_3$, about 16.2% of H_2O and a little Na_2SO_4 and NaCl. These lakes were formerly a commercial source of soda.[3]

Mono Lake has a salinity of 53.47 parts per thousand and contains about 300,000,000 tons of salts, of which over 100,000,000 tons are Na_2CO_3. It is interesting to

[3] Russell, I. C., "Geological History of Lake Lahontan, a Quaternary lake of Northwestern Nevada," U. S. Geol. Sur., *Mon.* 11, 1885, and Chatard, T. M., "Natural Soda; Its Occurrence and Utilization," U. S. Geol. Sur., *Bull.* 60, pp. 27–101, 1890.

know that 10,000,000 tons of KCl are also present in the lake water, although it is not available at present.

Owens Lake has an area of 97.2 square miles with a maximum depth of about 30 feet.[4] Its salinity varies with the season. In August of 1905 it was 213.7 parts per

FIG. 84.—Map of Nile Delta, showing positions of Natron Valley and Bitter Lake. (*Grabau's Principles of Salt Deposition, Fig. 54.*)

thousand. The lake water contains 8,000,000 tons of soda. It is now being used as a source of commercial Na_2CO_3. It is hoped soon to extract the potash from the waters of this and similar lakes, with the result that Na_2CO_3 will be obtained as a by-product.

A few operators are active in producing natural sodium carbonate of which three are on Owens Lake and one on Searles Lake but the amount of the material produced by

[4] Gale, H. S., "Salines in the Owens, Searles and Panamint Basins, Southeastern California," U. S. Geol. Sur., *Bull.* 580, pp. 251–323, 1914.

them is not known as it is reported together with the soda made by the Leblanc and Solvay processes.

The Natron Lakes of Egypt lie just to the southwest of the Nile delta (Figs. 84 and 85). During the rise of the Nile the greatest depth in some of the lakes is about 6 feet, but in May, June and July the lakes are mostly

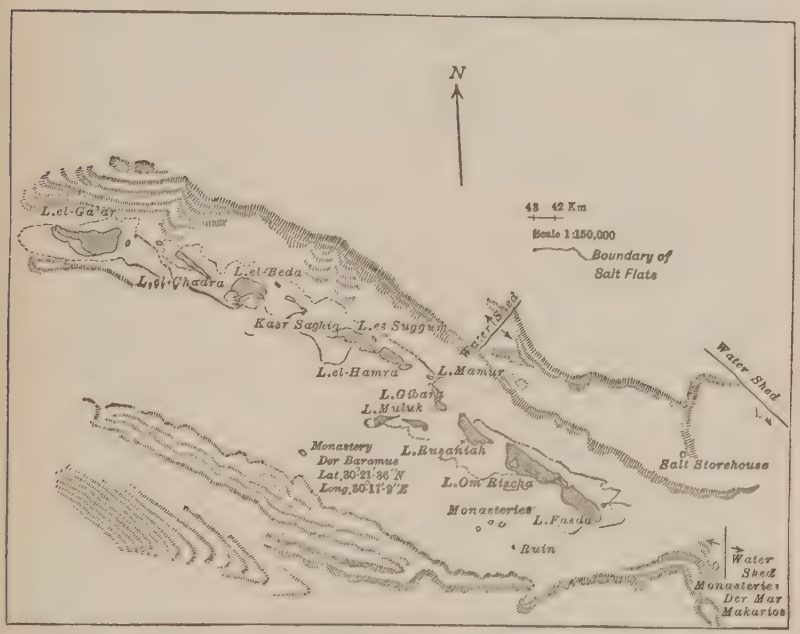


FIG. 85.—Map of Natron lakes, in Nile Delta. *(After Schweinfurth, Zeit. der Gesellschaft für Erdkunde, Berlin, Vol. 22, 1898.)*

dry, and their bottoms are covered with alternating layers from 10 to 27 feet thick of NaCl and $Na_2CO_3.10H_2O$ (natron), and their borders with an efflorescence of pure Na_2CO_3. It is not known how much of this material is present in the valley of the lakes, but it is enormous.

In the Magadi district in British East Africa one playa has been estimated to contain 200,000,000 tons of Na_2CO_3.

Some alkali lakes obtain their salts through the aid of

organisms. Just as some plants and animals secrete $CaCO_3$ from sea water, others take from the soil certain compounds dissolved in the ground water. Among these are many plants that secrete NaCl, Na_2CO_3 and compounds of potassium. When burned their ashes consist largely of these materials. Some of them have been burned for ages past to furnish alkalies for making soap.

The Kelpwort is widely spread on seashores of Europe, Asia and North and South America. In the salinas of Argentina it is especially prominent. Its ash, which is abundant, consists of

NaCl	19.38
K_3PO_4	21.15
K_2CO_3	7.80
Na_4SiO_4	7.86
Na_2CO_3	41.73
Others	2.08
	100.00

When a plant is burned its ash may amount to from 5% to 12% of the dry plant though, of course, in most cases it is much less. A bushel of dry ashes from wood may contain 2.9 lbs. of K_2O, 1.25 lbs. of P_2O_5 and 16 lbs. of CaO. The ashes of corn-cobs contain about 21.13% of K_2O, and 4.01% of P_2O_5. Beets contain 60 lbs. of K_2O and from 4 to 12 lbs. of P_2O_5 per ton and salt-marsh grasses from 14 to 42 lbs. of K_2O and 5.0 to 7.5 lbs. of P_2O_5.

Salt-secreting plants surround many of the lakes and playas in arid regions. When they die they leave their deposits of ash in the soil. These are leached by occasional rains and the salts are carried into the drainage basins where they accumulate.

The Soda Lakes of Armenia contain great quantities of sodium salts, a large portion of which is supposed to have

been leached from plant ashes. In Yellow Pool Water which has a salinity of 347.4 parts per thousand the salts are Na_2CO_3=68.90%; Na_2SO_4=15.55% and NaCl= 15.50%.

But the alkali lakes of most interest are those containing potash, since potash salts available for use in agriculture are not widely spread. Among the most important of these are the potash lakes of Nebraska.[5] They are small hollows amid sand dunes (Fig. 86), the deeper of which contain fresh water and the shallower ones salt water, in some lakes with a salinity of 135 per mille and over. The annual precipitation in the district is between 15 and 18 inches and the annual evaporation 60 inches. Consequently many of the lakes become dry during the summer. Their salts are believed to come from the surrounding country which used to be burned annually by the Indians.

Analyses of the water and of the muds and crusts from nearly desiccated lakes show the following results:

TABLE XL.—COMPOSITION OF THE SALTS IN THE WATERS OF SOME NEBRASKA LAKES

	K_2SO_4	K_2CO_3	Na_2CO_3	$NaHCO_3$	NaCl	Na_2SO_4
Lake 1.....	41.63	....	28.51	9.97	9.49	10.39
Lake 5.....	27.07	20.83	32.37	11.99	6.55	....

The mud in the lakes and around their margins is saturated with salts. At 1 foot below the surface of Jesse Lake, 40 feet from shore, the soluble constituents were 9.35% of the entire mass and of this amount 25.42% was K_2O. At 4 feet below the surface the soluble constituents were 4.63% of the mud, containing 28.92% K_2O. The

[5] Ziegler, V., "The Potash Deposits of the Sand-hills Region of Northwestern Nebraska," Colo. School of Mines, *Quart.*, Vol. 10, No. 3, pp. 6–26, 1915.

Hicks, W. B., "Potash Resources of Nebraska," U. S. Geol. Sur., *Bull.* 715, pp. 125–139, 1921.

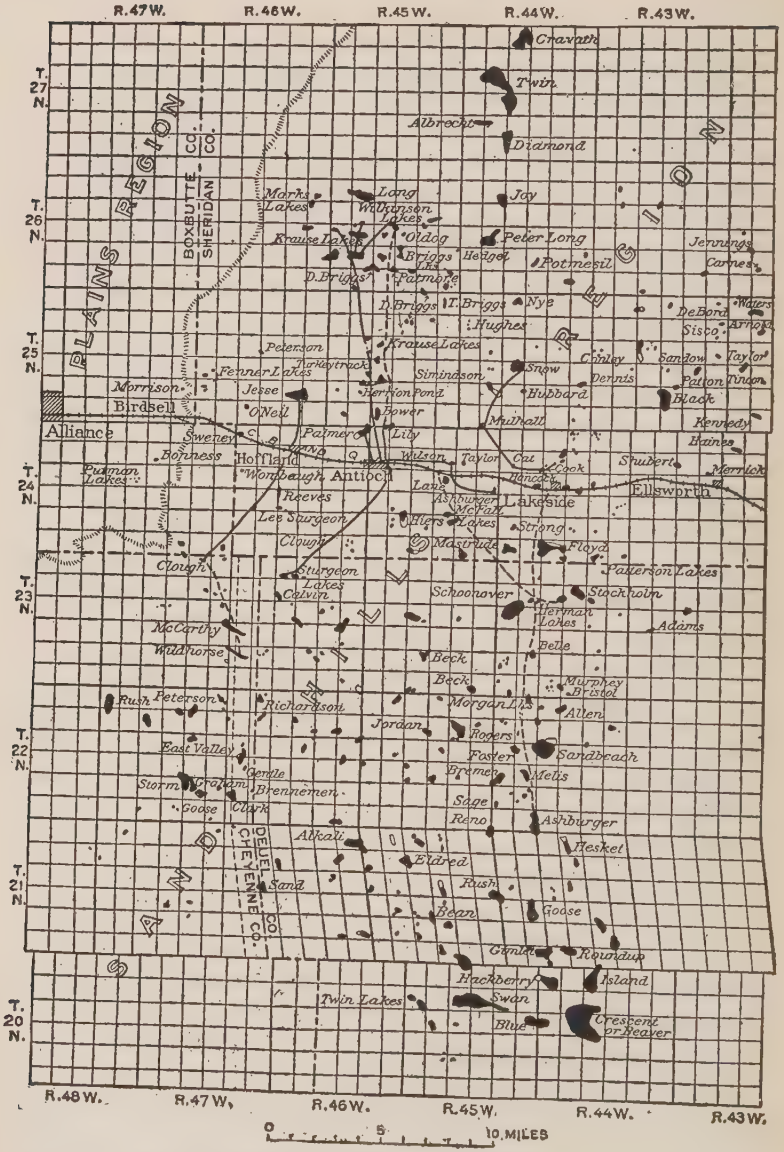


FIG. 86.—Map of potash lakes in western Nebraska. (*After Nebraska Conservation and Soil Survey.*)

crust at the margin of the lake contained 34.06% of soluble constituents, of which K_2O was 21.00%.

The total quantity of potash in all the Nebraska lakes is estimated to have been equivalent to 215,000 tons of K_2O.

Some of these lakes were formerly worked for potash, but they are now inactive. In 1918 they produced about 53% of all the potash made in the United States, or a total of 107,888 tons. Most of the product was in the form of mixed salts and fertilizer materials valued at about $12,000,000.

Borax lakes.—A few lakes contain considerable quantities of borax in solution, and formerly some of them were worked for this product. The borax of some of the lakes was probably obtained from the alteration of rocks containing the mineral tourmaline, but as this mineral is in comparatively small quantities it is not likely that many lakes obtained their borax in this way. To other lakes the boron was probably contributed by spring water containing constituents obtained from magmatic vapors.

The best-known borax lake is Borax Lake in the Valley of California. Its water has a salinity of 76.56 per mille, made up mainly of sodium carbonate and potassium and sodium chlorides, but 12.6% of the total salt content is borax. Borax crystals occur in the muds around the shores of the lake, but no bedded deposits of the mineral have been found beneath the water. A neighboring spring yields water with a salinity of 5.34 per mille, nearly all of which is borax.

CHARACTERISTIC PLAYA DEPOSITS

In the playas (Fig. 91), or salt-marshes, are found nearly all the salts occurring in the mother liquors of desert lakes, either as deposits, or in brines saturating their soils. In addition, playas contain also other salts that have not yet been found in commercial quantities in lake waters.

The compounds represent not only primary salts, but also those produced by the decomposition of the rocks within the inland drainage basins of which the playas are a part, and those contributed by wood ashes.

All the playas in the arid regions of the United States contain large quantities of Na_2CO_3, Na_2SO_4 and NaCl and other compounds which are different in different portions of the general area. A few analyses of the incrustations from some of these playas will illustrate their variety.

TABLE XLI.—COMPOSITION OF INCRUSTATIONS FROM SOME PLAYAS

	Na_2CO_3	Na_2SO_4	NaCl	K_2SO_4	$Na_2B_4O_7$	$NaNO_3$	NaH_2PO_4
Humboldt Lake	18.15	49.67	20.88	....	11.30	.....	....
Merced Bottoms	75.95	4.67	1.46	....	.....	12.98	4.94
Visalia.....	65.72	.....	3.98	20.23	.....	.....	8.42
Ruby Valley...	66.78	28.32	2.11	2.79	.....	.....	....

Among the most important playas in the United States are Columbus Marsh and Rhodes Marsh in Nevada and Death Valley and Searles Marsh in California. (See Fig. 82.)

Columbus Marsh.—Columbus Marsh is a mud flat about 40 square miles in area surrounded by salt efflorescences. The mud contains about 20.5% of K_2O in the water-soluble portions of the sample. Formerly the incrustations were collected and refined for borax.[6]

Rhodes Marsh.—Rhodes Marsh, about 7 square miles in area, is underlain by deposits of rock salt, Glauber's salt and sodium sulphate. Incrustations of borax or tincal, 1 to 3 inches thick, occur at the surface of the mud, and crystals of the same mineral are scattered through it. Aggregates of ulexite ($CaNaB_5O_9.8H_2O$) are embedded in a stiff clay. Two analyses of the mixtures of sand,

[6] Gale, H. S., "Potash Tests at Columbus Marsh, Nevada," U. S. Geol. Sur., *Bull.* 540, p. 422, 1914.

organic matter and salts that constitute the incrustations show:

TABLE XLII.—COMPOSITION OF INORGANIC PORTIONS OF INCRUSTATIONS OF RHODES MARSH, NEVADA

	Na_2SO_4	Na_2CO_3	NaCl	Borax and Calcium Borate
Over an area of 40 acres..	16.00	5.00	8.07	41.22
Over an area of 100 acres..	10.70	.....	9.00	63.00

The boron compounds are furnished by springs.

Death Valley.—In Death Valley is a belt of Tertiary sediments consisting of clay, sand and gravel, volcanic tuffs, etc., and interbedded with them is a 20-foot thick mass of colemanite ($Ca_2B_6O_{11}.5H_2O$) consisting of irregular masses and stringers embedded in clay.[7] The valley receives the water of several streams but although it is about 275 feet below sea level it has never been a lake. The water evaporates so rapidly that the floor of the valley remains dry except in very rainy seasons. Its deeper portions are covered with immense deposits of salts, and muds and salts interlayered. The salts are mixtures of about 95% NaCl, 3.50% Na_2SO_4 and 1.50% of other compounds. In some places colemanite is also present near the surface, but this is believed to have been derived by solutions from the Tertiary mass already referred to and redeposited. Until recently this surface deposit was worked for borax.

Searles Marsh.—Searles Lake, or Searles Marsh, in San Bernardino County, California, is probably the most interesting of all the playas at the present time because of the possibility that it may prove an important source of potash. The surface of the playa occupies about 60 square

[7] Gale, H. S., "Prospecting for Potash in Death Valley, California," U. S. Geol. Sur., *Bull.* 540, p. 407, 1914.

miles, but the main salt deposit, which is 70 feet thick, covers only 11 or 12 square miles[8] in the lower portion of a basin formerly occupied by a lake 640 feet deep. The salt crust consists of halite, thenardite (Na_2SO_4) and borax. As fast as it is removed capillarity draws other salts from the depths, which in turn effloresce at the surface and replace the material removed. Borax was produced here in large quantity for some years until the discovery of great deposits of colemanite offered a cheaper source for boron salts.

The interstices between the salt crystals in the center of the marsh and between the mud particles elsewhere in the basin are saturated with a brine which contains the following ingredients.

$NaCl$	Na_2SO_4	Na_2CO_3	$Na_2B_4O_7$	KCl	Others
51.61	19.22	12.79	3.23	12.07	.17

Estimates indicate that the brine known to be present contains 20,000,000 tons of K_2O. It is now being worked yielding annually about 2,400 tons of high grade potash salts.

Sections through the muds reveal alternating layers of mud, various salts and of salts mixed with mud.

A list of the solid salts found in the deposits includes 6 sulphates, 2 borates, 6 carbonates, 1 chloride, 1 borosilicate and 4 triple salts. The potash salts occur only in the mother liquor (brine). It is notable that only 5 of these salts are found also in the Stassfurt deposits, which are precipitated from ocean water. The other 15 are not known at Stassfurt. On the other hand, there are many salts in the German beds that are not in these Searles Lake beds. Consequently, it is inferred that the two

[8] Gale, H. S., "Notes on the Quaternary Lakes of the Great Basin, with Special Reference to the Deposition of Potash and Other Salines," U. S. Geol. Sur., *Bull.* 540, p. 405, 1914.

deposits were different in origin. Since the Stassfurt salts were undoubtedly deposited from sea water, it is inferred that the Searles Lake deposits originated in solutions that must have been produced by the alteration of the neighboring rocks.

SPRING WATER DEPOSITS

Spring waters obtain their dissolved constituents either by solution of the rocks through which they pass, by decomposition of these rocks and the leaching of the resulting soluble products, or by contributions furnished by juvenile waters.

Geysers are hot springs that erupt periodically. Fumaroles may be regarded as springs in which volcanic vapors and steam are intermingled.

Cold springs deposit little material. They originate near the surface and because of its low temperature their water causes little alteration of the rocks through which it passes and consequently carries comparatively little material in solution. Calcareous sinter and stalactites are the commonest deposits, but some magnesium carbonate is often deposited with the calcium carbonate, and in some places small amounts of arsenic compounds, barite, silica, iron sulphate, manganese oxides and hydroxides and in rare instances fluorite. Where the water contains much magnesium the calcium carbonate usually deposits as aragonite and where it contains iron carbonate, this material oxidizes in contact with the air, and iron hydroxides are precipitated. In a few places manganese oxides are extracted from spring water by organisms. None of these substances, however, occur in sufficiently large deposits of material pure enough to be of commercial importance, except stalactite, which when sawed and polished is used as an ornamental stone under the name Mexican onyx.

On the other hand, deposits are common around the orifices of hot and warm springs. Some thermal springs obtain their material from the decomposition products of the rocks through which their water passes and others by accessions from magmatic waters. Consequently their water varies widely in composition. Analyses of the salts contained in some famous springs and of those in the ground water traversing some ore deposits are quoted below from Clarke's "Data of Geochemistry":[9]

TABLE XLIII.—COMPOSITION OF THE CONSTITUENTS IN CERTAIN SPRING WATERS

(References are to U. S. Geol. Sur., *Bull.* 770)

	A	B	C	D	E	F
Cl	58.85	58.79	56.58	35.00	3.73	....
Br	.01	....	.04	....	....	....
B_2O_7	....	....	....	8.88	....	....
SO_4	2.29	.94	.78	4.58	74.16	76.57
CO_3	....	.61	3.13	5.08	.03	....
SiO_2	....	....	....	11.41	....	1.39
Na	37.29	30.38	32.60	30.35	4.50	1.19
K	.03	3.76	1.16	3.79	.03	....
Ca	1.28	4.90	4.05	.25	.02	5.82
Mg	.23	.40	.61	.02	17.45	3.39
Various	.01	.22	1.06	.66	.08	Fe 4.28 Al 7.36
	100.00	100.00	100.00	100.00	100.00	100.00
Salinity pts. per million	168,400	23,310	8,241	2,850	101,000	3,303

A. Brine from Syracuse, N. Y. Average of 4 analyses. P. 184.
B. Utah Hot Springs, Missouri. P. 185.
C. Kochbrunnen, Wiesbaden, Germany. P. 186.
D. Steamboat Springs, Nev. P. 188.
E. Cruzy, Herault, France. In gypsum quarry. P. 189.
F. Alum well, Versailles, Mo. P. 190.

[9] F. W. Clarke, "Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, 1924.

	G	H	I	J	K	L	M
Cl.....	8.85	6.17	2.42	.28	1.27	31.64	.34
F.....	.19	....	.....	....	....	Br .25	.....
SO_4....	5.77	3.75	.54	1.68	3.93	1.30	55.08
CO_3....	41.91	45.57	55.92	38.72	41.47	8.78	H_2SO_4 16.62
Na.....	38.08	35.27	1.92	1.36	2.38	26.42	.....
K.....	1.20	2.88	.73	.46	.80	1.93	.57
Ca.....	.87	2.29	29.28	17.18	23.54	.11	2.91
Mg....	.41	1.11	3.15	4.89	2.56	.04	.55
Fe.....	....	....	2.28	17.24*	....	....	3.47
SiO_2....	2.30	1.32	2.42	17.97	22.85	27.58	12.72
Various acids	.17	1.56	(Mn .91)	.14	.90	1.43	(NH_4 .58)
Various metals	.25	.08	(Al_2O_3 .43)	.08	.30	.52	Al 7.16
	100.00	100.00	100.00	100.00	100.00	100.00	100.00
Salinity per million	2,614	5,249	489	622	199	1,388	2,477

* Fe_2O_3.

G. Ojo Caliente, near Taos, New Mexico. Pp. 192–3.
H. Grande-Grille, Vichy, France. Pp. 192–3.
I. Excelsior Springs, Mo. Pp. 192–3.
J. Wilhelmsquelle, Karlsbrunn, Silesia. Pp. 192–3.
K. Big Iron Springs, Hot Springs, Ark. P. 196.
L. Old Faithful Geyser, Yellowstone. Pp. 196–7.
M. Solfatara, Pozzuoli, Italy. P. 200.

Much of the material contained in the water of hot springs is obtained by solution of the rocks through which their conduits pass. The water of such springs, especially if acid, may profoundly alter the rocks with which it comes in contact, leaching them of some of their components and carrying the soluble products, which are mainly chlorides, sulphates and carbonates, to the surface. This process is especially noticeable if the rocks traversed by the springs are limestone, which furnishes much of the calcium carbonate in many spring-waters.

TABLE XLIV.—COMPOSITION OF THE SALTS IN CERTAIN MINE WATERS

(The page references are to U. S. Geol. Sur., *Bull.* 770)

	(1)	(2)	(3)	(4)
Cl	.03	.48	.16	.01
SO_4	70.93	52.76	64.47	60.29
CO_3	....	8.00	....	....
PO_4	.23	....	....	....
H_3AsO_4	1.93	....	....	....
Na	1.25	.67	1.14	.04
K	.23	.46	.10	Tr.
Ca	7.08	11.32	14.38	.26
Mg	.93	.71	1.36	.13
Mn	.78	.42	.08	.01
Fe	11.12	.11	6.49	.04
Al	3.09	.08	.20	.07
Zn	....	22.31	10.74	Cu 38.72
Var. Metals	.79	.14	.02	.37
SiO_2	1.61	2.54	.86	.06
	100.00	100.00	100.00	100.00
Salinity, parts per million	8,150.00	540.00	4,232.00	117,850.00

(1) Rocegno, Tyrol. From arsenical pyrites. P. 190.
(2) Shoal Creek. From deposits of sphalerite. P. 190.
(3) Mine Water. From Missouri zinc region. P. 191.
(4) Mountain View Mine. Butte, Montana. P. 190.

Although the waters of warm and hot springs deposit many compounds only a few of the deposits are of commercial importance. Slight traces of cinnabar, ocher, manganese oxides and other compounds are known to have separated around the exits of hot springs and larger quantities of sulphur, boron compounds, calcium carbonate and silica. The last two of these compounds are formed in rough porous masses which are known as sinters. The calcareous sinter, which has no important use, results, as in the case of cold springs, from the escape by evaporation of CO_2 from carbonated waters containing

$CaCO_3$ in solution, or is removed by organisms. Siliceous sinter deposits around the orifices of geysers and other hot springs erupting alkaline water. Thus the dissolved material in the water of the Old Faithful geyser contains 27.58% of SiO_2, and that of the Sprudel, Karlsbad, 45.04% of SiO_2. The deposits around these springs result in part from cooling and relief of pressure, and in part through the action of algæ that live in the hot waters. In some places the silica deposited around hot springs is used as an abrasive, but it is not generally exploited commercially.

Sulphur occurs around some hot springs as a result of the reaction of H_2S, brought up by the spring water, and the air ($H_2S + O = H_2O + S$). It has been collected from around springs in Nevada and elsewhere but not in great quantity.

Boron compounds are common around some hot springs that issue in volcanic regions. The boron is of solfataric, or fumarolic, origin. In Italy borax is collected from the pools in the neighborhood of some fumaroles.

SALT

Halite, or common salt (NaCl), is the most important of the salines. It occurs in large quantities dissolved in the water of the ocean and of many lakes, in the brines saturating layers of rock and also as great solid masses (rock salt) interstratified with other rocks.

ROCK SALT

The deposits of rock salt that are so widespread over the earth are believed to be the result of the evaporation of the water of the ocean or of salt lakes. No salts are precipitated from the ocean water until its volume has been materially reduced. Before precipitation can take

place a portion of the sea must be isolated. Under conditions thus produced evaporation from its surface may exceed the amount of water supplied by rain and snow, by streams and by springs. When the volume of the solution is reduced to a little less than one-fifth of its original volume, gypsum will fall from it and when reduced to a little less than one-tenth salt will begin to separate. (See p. 12.)

Salt pans.—If there is a recurrent access of the sea to basins containing pools of concentrated sea water on coasts, there may be alternate precipitation and solution of gypsum and salt. If mud is deposited on the salt layers solution may be retarded or prevented and a fair thickness of salt may result. This is what happens in the "salt pans" of the Rann of Cutch, near Bombay, India, those of the Red Sea coast of Eritrea, and those of the Nile Delta and the Black Sea coast.

When the sea invades the pans it carries into them marine plants and animals, which being unable to exist in the salt solution die and leave their remains to accumulate in the gypsum layers deposited upon the underlying salt. This recurrence of gypsum and salt and the association of fossils with the gypsum characterize deposits of this kind.

A small quantity of salt is obtained from the salt pans, but only for local use.

Marine salinas.—In some places sea water seeps through barriers and fills depressions in the land, forming "marine salinas." These are marine salt lakes. Such lakes occur on the Isle of Cyprus, in Cuba, on the peninsula of Araya in Venezuela and in Roumania near the Black Sea. During winter, when evaporation is slow the depressions are occupied by lakes. In summer evaporation exceeds the supply by seepage and incrustations of salt are formed. During the seepage the more difficultly

diffusible salts, like calcium sulphate, are in large measure prevented from entering the basin and as a result only halite (NaCl), sylvite (KCl) and a few double salts are deposited.

These are laid down in beds that can never be very thick unless the land sinks gradually while at the same time the barrier is growing in height at the same rate. Moreover, no gypsum layers are associated with the salt nor are any visible fossils present.

The marine salinas of Venezuela and Cyprus yield an excellent quality of salt to the natives in their vicinities, but they are not important sources of the commercial product.

Lagoon deposits.—One of the most important types of salt deposits is that formed in lagoons, where great thicknesses of halite and other ocean salts may be laid down under favorable conditions. Salt pans and marine salinas can never deposit great thicknesses of salt comparable to some of those known to exist in sedimentary rocks. In some places in the United States and elsewhere are immense deposits of rock salt and some gypsum, with very little admixture of the magnesium and potassium salts so abundant in sea water. They evidently were precipitated without complete evaporation of the water in which they had been dissolved.

To account for such deposits Ochsenius has suggested a "bar theory" which is now undergoing critical study by a number of geologists. According to this theory a lagoon was separated from the main ocean by a bar through which a constant or nearly constant connection between the two bodies of water was maintained by shallow inlets allowing only sufficient water to enter the lagoon to compensate for that lost by evaporation. Since the inflowing current would carry a constant amount of salt, it is plain that the salinity of the water in the lagoon

would increase, provided it were not fed by rivers or springs. The salinity would finally reach the point at which gypsum would be deposited and then rock salt. The most abundant gypsum precipitation would occur near the inlet whereas thinner beds would be deposited with the salt elsewhere. If the inlet were then closed all the gypsum would after a while be deposited and thereafter only pure salt would be separated. A renewed incursion of the sea would result in cessation of deposition, followed by a resumption of deposition, first of gypsum and later of rock salt—the thickness of the salt beds varying with the length of time during which the inlet was closed. If muds should enter with the sea when the barrier was breached, a layer of silt would deposit over the salt and protect it, and this would be followed by gypsum. If the lagoon should dry completely potassium and other salts would finally be thrown down. However, in most cases complete evaporation does not take place as potassium salts are rarely found with rock salt deposits.

The Karabugus Gulf on the east side of the Caspian Sea is regarded as a modern salt lagoon (Fig. 87). It is about 80 miles long and 70 miles wide and is separated from the Caspian Sea by sand spits between which is a narrow inlet about 100–500 yards wide. A constant current flows through this into the gulf at a rate varying between 25 and 50 yards per minute carrying with it 1.07 million cubic meters of water per hour, or a daily load of salt estimated at 350,000 tons. The gulf water is thus constantly becoming more saline. At present the salinity of the sea is 12.94 per mille and that of the gulf 285 per mille.

Grabau,[10] however, points out the fact that salt deposits formed by the method outlined would be accompanied by abundant fossils, since many animals would be swept

[10] Grabau, A. W., *Principles of Salt Deposition.* New York, 1920. Pp. 137–139.

into the lagoon by the current through the inlet and being unable to return would die. He quotes Andrussow as

FIG. 87.—Map of Karabugus Gulf, Caspian Sea. (*After Seidlitz, modified by Grabau, Principles of Salt Deposition.*)

stating that dead fish and even dead seals are found on the shores of Karabugus Gulf, the former in such quantities that the gulls feed only on their eyes. Consequently

it is thought the bar theory cannot be used as an explanation of thick deposits of rock salt without fossils, but may be the proper explanation of those in which fossils occur.

Branson [11] attempts to get rid of the difficulty which Grabau emphasizes by supposing the depositing lagoon to be separated from the ocean by two or more intervening lagoons, in the first of which the fossils would be deposited and in the second most of the gypsum, leaving the third for the accumulation of the pure salt. The great salt deposits of Wieliczka, in Galicia, are supposed to have been formed in this way as perhaps also those of Kansas and of some other portions of the United States.

Cut-off bay deposits.—Other deposits, especially those in which magnesium and potassium salts are present, are believed to have been deposited in portions of the ocean entirely cut off from the main body of water in arid regions. Such a body of water would contract as evaporation proceeded. Gypsum and rock salt would form over comparatively wide areas, but the mother liquor would concentrate in the lowest portions of the basin, and if evaporation continued, many substances would finally precipitate and the character of the salts formed would be determined largely by the temperature at which the evaporation took place. (See pages 13 and 14.) Thus kieserite ($MgSO_4.H_2O$) and sylvite would be formed only above 72°, glauberite ($CaSO_4.Na_2SO_4$) above 10°, etc.

The Salton Sea in Lower California is regarded as affording an illustration of this process. It was separated from the Gulf of California by the building of a delta at the mouth of the Colorado River. From a careful consideration of the history of this sea, it is evident that fossils must underlie the basin. Since, however, the life became

[11] Branson, E. B., "Origin of Thick Gypsum and Salt Deposits," Geol. Soc. Am., *Bull.* 26, pp. 231–243, 1915.

extinct when the water had been concentrated to a high salinity, but before it began to deposit salts, the fossils must be spread over the entire area of the bottom of the cut-off body. There can be no regularity in the fossiliferous series under the salt, as this would be confined mainly to the deeper portions of the basin. Thus, the salt might come to rest directly upon marine deposits, but separated from them by gypsum, and perhaps by a series of clastic strata without fossils. Outside the area of the salt however, the fossiliferous series must pass upward into unfossiliferous terrestrial deposits such as delta and flood-plain deposits that were made around the borders of the contracted sea.

In bodies of water like this the mother liquor salts where deposited will have a much more restricted distribution than the common salt, since they would be confined to the deeper depressions. The great deposits of various salts at Stassfurt, in Germany, in Alsace and in Spain are of this type. (See pages 289-295.)

Salt domes.—Salt domes, as already described, are masses of salt that have been forced upward into overlying beds, deforming their original horizontal layers into flat dome-like folds and in some places into sharp anticlines. The salt has probably come from beds of salt lying at a much lower horizon. In their ascent they have been folded into sharper corrugations than the overlying sediments. (See pages 74–77.) Barton[12] states that there are probably 117 known salt domes and salt ridges in the United States, 15 in Mexico, 60 in old Roumania, 15 in Transylvania, 50 in Germany and others in Spain, Northern Siberia, at the south end of the Ural Mountains, in Algeria, in Egypt and in Persia. (See maps and sections, Figs. 29, 43 and 94.)

[12] Barton, D. C., "The Economic Importance of Salt Domes," University of Texas, *Bull.* 2801, pp. 7–53, July, 1928.

BRINES AND THEIR DEPOSITS

Salts are produced not only from the water of existing seas and the ocean, but also from sea water that was buried with certain sediments, i.e., from connate sea water.

Brines.—If a rock saturated with sea water contains 30% pore space and the average salinity of sea water is 35 per mille the average amount of sea salt enclosed in the rock is about 1% by volume. A marine limestone of this porosity 1,000 yards thick might enclose enough salt to make a bed 3.65 yards thick, or if the salt content of such a bed covering 5,000 square miles were concentrated in an area of 100 square miles, a bed 182.5 feet thick would be formed.

So long as beds containing connate brine remain beneath the level of circulating waters they retain their brine, which may be reached by deep wells and may become sources of commercial salts, though common salt is not commonly extracted from them, except as a by-product, because of the expense of separating it from the complex solution.

When raised above sea level, however, the connate brines enter the zone of circulating waters. Some of their salts are carried to the sea. If, however, drainage is toward inland basins they may produce the salt lakes, which are so common in desert regions, such as the Lop-Nor in Chinese Turkestan, the numerous lakes of the Kewir desert in Persia, etc., and some of those in the Great Basin. (See also page 232.)

Lake deposits.—In deposits from salt lakes of this kind, there is not to be expected the presence of mother liquor salts, even where the lakes have nearly dried, since potash and magnesia salts are not as common in connate brines as in modern sea water, because they do not diffuse

through the pores of the rocks as easily as does NaCl. Moreover, the potash is utilized more rapidly by vegetation. Moreover, since the mother liquor salts are the last to solidify they are apt to remain for some time on the surface from which they are blown away with the dust in the fierce windstorms of desert regions.

The calcium sulphate of the brine precipitates in the hot sands as gypsum crystals that are so abundant around desert lakes, and the water that reaches the lakes contains little $CaSO_4$. Gypsum beds are, therefore, rarely associated with salt deposited from desert lakes. If any sulphate should precipitate it would separate rather as anhydrite than as gypsum, since this salt crystallizes only below 30°, or perhaps 25°, when NaCl is present in its solutions.

Around the margins of the lakes are efflorescences of salt. This and the gypsum which is found in the sands around the lakes is sometimes blown into dunes. The gypsum dunes are exploited and the material is shipped under the trade name "gypsite."

The best known salt lakes in this country are Great Salt Lake, which is a remnant of the greater Lake Bonneville, and Sevier Lake, Utah (Fig. 88). The composition of their dissolved salts is shown by the following figures:

	Cl	SO_4	Na	K	Ca	Mg	Salinity per Mille
Salt Lake, 1904	55.25	6.73	34.65	2.64	.16	.57	277.2
Sevier Lake	52.66	10.88	33.33	....	.12	3.01	86.4

These lakes contain deposits of halite, especially around their borders, and of $Na_2SO_4.10H_2O$ (Glauber's salt) in dry deeper portions. Potassium salts are usually lacking from the deposits though they may be present in the remaining mother liquor.

Other salt lakes of this type, i.e., in which the salt is from connate brines are in the arid regions of Chile and

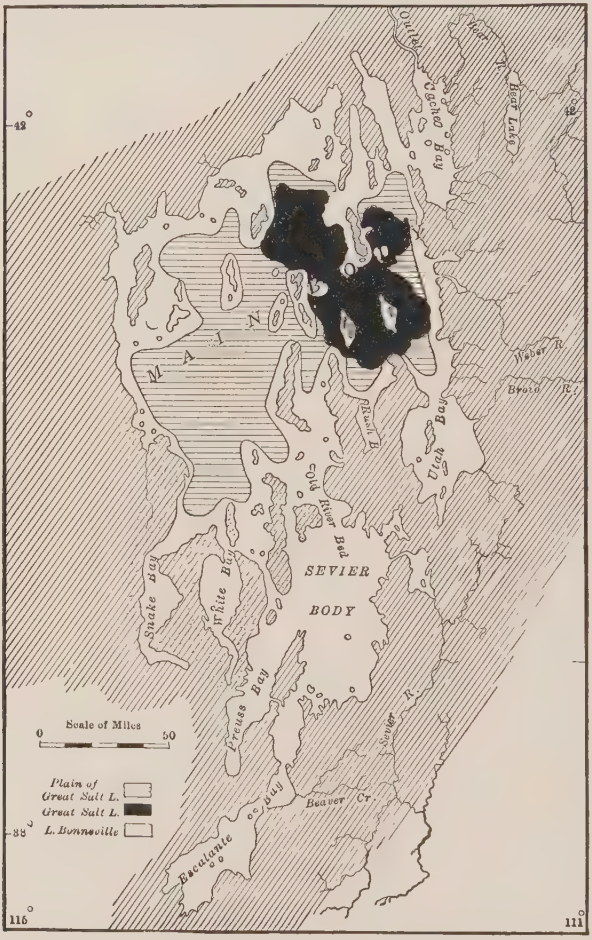


FIG. 83. Map of Lake Bonneville and Great Salt Lake, Utah. (*After Gilbert. Redrawn by Grabau, Principles of Salt Deposition.*)

Argentine, Australia and Africa, and the salt "vleys" in the southern portion of the last-named continent. These correspond to "salt pans" but they are inland and they

obtain their salt from the surrounding soil, rather than directly from the sea.

The deposits from lakes of this kind furnish salt locally.

Other salt lakes derive their salt from the solution of beds of rock salt buried in the rocks. Their salinity is secondary. They differ in origin from the lakes just described in that in the latter the salt was never deposited as a bed but remained diffused through the rocks, while in the former the salt was once precipitated from bodies of water by complete or nearly complete evaporation. Lakes of this kind may contain not only NaCl in their water, but also magnesium and calcium chlorides and carbonates.

The Dead Sea in Palestine which has a salinity of 192 per mille at its surface and 260 at a depth of 300 meters is thought to be a lake that has derived its salt from marine deposited salt beds.

The salts deposited from its water taken at a depth of 300 meters yield upon analysis:

Cl	Br	SO_4	CO_3	Na	K	Ca	Mg	SiO_2
67.30	2.72	.24	Tr.	5.50	1.68	6.64	15.92	Tr.

Elton Lake near the Caspian Sea in Russia is another lake of this kind. The total amount of salt carried into it annually is 19,500 tons, and on its bottom is a thinly stratified salt layer over 12 feet thick. The salt is nearly pure (96.6% NaCl) and has furnished about 85,000,000 tons during the past 150 years.

In the deposits of all lakes of this type gypsum is usually lacking or is present in small quantities only. If present in the original salt beds most of it has been left behind, or has been delayed in its passage through the rocks by its comparatively low diffusibility.

One type of salt lake is rather unusual. The wind blows

salt spray inland. Thus at Rothamstead, England, 24 lbs. of NaCl are blown on to each acre annually, at Perugia, Italy, 37.95 lbs. and in British Guiana near the coast, 195 lbs. Wherever salt is carried by the wind into regions of interior drainage it must accumulate. Salt lakes may thus be formed in which nearly all the salt comes directly from the sea. Sambhar Lake in Northern India is a salt lake of this kind. It is shallow and obtains from the air 3,000 tons of salts annually.

The dissolved constituents in its water are:

Cl	Br	SO_4	CO_3	Na	K	Cu	Mg	SiO_2	Total
52.96	.04	5.85	2.19	36.86	.09	Tr.	.01	Tr.	100.00

In the hot months the water evaporates and salt is deposited. To the natives the lake furnishes about 170,000 tons of halite annually, some of which is obtained from the exposed floor of the lake as it evaporates. The rest is obtained from the brine by the solar evaporation of the brine caught in pans.

PRODUCTION AND OCCURRENCES

Most of the salt of commerce is obtained (a) from ocean and lake waters by artificial evaporation, (b) from connate brines, and (c) from beds and efflorescences left by the natural drying of ocean or lake water, or of water saturated by the solution of the salt derived from fossil lagoons, salt pans or lakes.[13] The common salt from lagoons is usually associated with salts of magnesium and potassium which, in some localities, are of commercial importance.

United States—*Production.*—The salt produced in the United States, from a total of 92 plants, during

[13] Phalen, W. C., "Technology of Salt Making in the United States," U. S. Bur. of Mines, *Bull.* 146, 1917.

1927 aggregated 7,586,690 short tons[14] valued at about $25,000,000.

Of this amount:

2,143,860 tons were rock salt obtained mainly in New York, Kansas, Louisiana, Texas and Michigan.

2,263,030 tons were made by evaporating brines, mainly in Michigan, New York, Ohio and Kansas, and

3,161,800 tons were furnished to chemical works in brine.[15]

Salt to the value of $1,329,980 was exported, principally to Canada, Mexico, Cuba and Australia, and a small quantity, valued at $167,675, was imported, mainly from Spain, Great Britain, and the West Indies.

Of the total salt and brine marketed in 1927 the principal producers were:

TABLE XLV.—PRINCIPAL PRODUCERS OF SALT AND BRINE IN 1927

	Tons	*Value*
Michigan	2,271,460	$7,551,552
New York	1,964,080	6,121,461
Ohio	1,203,170	3,130,236
Kansas	794,780	2,971,544
Louisiana	606,110	2,167,220
California	300,880	1,827,750

Rock salt was produced in eight States, with New York, Kansas, Michigan and Louisiana yielding 99% of the total.

Occurrence.—The salt in New York occurs in great lenticular bodies of rock salt in the shales of the Salina series (Silurian). Here it is associated with gypsum, and

[14] A barrel of salt weighs 280 lbs. or 8 barrels to the long ton.

[15] Phalen, W. C., "Salt Resources of the United States," U. S. Geol. Sur., *Bull.* 669, 1919.

Stone, R. W., "Salt, Bromine and Calcium Chloride: Our Mineral Supplies," U. S. Geol. Sur., *Bull.* 666, p. 42, 1919.

is either mined as rock salt or is raised as artificial brine, made by forcing water down into the salt layers. Some of the beds are very thick, one at Tully measuring 325 feet (Fig. 89).

In Michigan the salt is obtained partly as rock salt and partly from natural brines in the sandstones of the Mississippian series in the Saginaw Valley. Large quantities are also made from artificial brines produced by pumping lake water into the rock salt of the Salina beds along the Detroit and St. Clair rivers.

In Ohio natural brines are pumped from the Mississippian rocks at Pomeroy, and in northeast Ohio artificial

FIG. 89.—Interior view of rock salt mine, Livonia, N. Y. Roof and pillars are rock salt. (*After Ries, Economic Geology.*)

brines are made from a bed of rock salt 148 feet thick in the Salina.

In Kansas the commercial salt comes mainly from rock salt beds in the Permian and from brines in the Carboniferous (Fig. 90). In Louisiana and Texas it comes mainly from the Salt Domes. The greater part of that made in California was by the solar evaporation of sea water.

Very large deposits of rock salt occur with Permian and Triassic beds in western Texas and southeastern New Mexico, and in the salt domes of southeastern Texas and coastal Louisiana, where the salt has been intruded into Tertiary and perhaps Cretaceous sediments. Very little salt has been produced from New Mexico and western Texas, but the salt domes on the coastal plains of Texas

FIG. 90.—Interstratified shale and salt, Bevis Rock Salt Co.'s Mine, Lyons, Kansas. (*Photo by S. Ainsworth, U. S. Geol. Sur., Bull. 669.*)

and Louisiana yield annually about 370,000 metric tons, valued at about $2,000,000. Barton estimates that 10 of the salt domes in these two States contain easily minable reserves that would satisfy the world demand for salt for 4,000 years.[16]

WORLD.—The world's production of salt in 1926 was about 25,000,000 metric tons, not counting that used locally.

[16] Barton, D. C., "The Economic Importance of Salt Domes," Univ. of Texas, *Bull.* 2801, pp. 7–53, July, 1928.

TABLE XLVI.—PRINCIPAL SALT-PRODUCING COUNTRIES AND THEIR PRODUCTION DURING 1926

	Metric Tons
United States	6,687,268
China	3,600,000
Germany	2,535,120
Great Britain	1,744,016
France	1,700,000
British India	1,528,026
Russia	1,457,202
Spain	1,097,268
Japan	857,366
Italy	766,252
Poland	457,503

The distribution of rock salt and brines throughout the world is so very wide-spread that no attempt will be made to describe even the best known localities. It is probable that every salt lake is a source of salt for local uses and the ocean is a general source for all countries bordering on it.

The evaporation of sea water furnishes most of the commoner grades of salt used in Mexico, Central America, West Indies, Argentina, Brazil, and Venezuela, and beds of rock salt the greater part of the production in the United States, Canada, Chile and Colombia.

The great producers of the world outside of North America are England, in Cheshire, Germany at Stassfurt, Austria at Salzburg, Russia in the Donetz Basin in Orenburg, China and India. In some of these countries a large part of the production is from ocean water but in England, Austria and Germany, it is nearly all mined from beds of rock salt.

The mines in Germany are particularly noted not for their salt but for the associated potassium compounds. They will be referred to in some detail later. (See pages 289–292.)

In Europe most of the salt beds are Permian or Triassic,

the most notable exception being the famous Wieliczka beds in Galicia, Poland, which are Miocene. The most important deposits in Asia are in the Salt Range, Punjab, India, where they are in folded rocks, probably of Silurian age, and in China, where they are probably Devonian.

Much of the salt produced in Germany, Rumania, and Spain is from salt domes.

RESERVES

There are no accurate estimates of the world's reserves of common salt, but Barton believes that the reserves in the salt domes of the world would suffice for the world demand for 300,000 years, at the present rate of consumption, and that this amount is only about 5% of the world's entire reserve.

BROMINE AND BROMIDES

After the extraction of salt from some natural brines there is left a bittern which contains small quantities of bromine.[17] The richest of these occur near Saginaw Bay and Bay City in Lower Michigan, at Pomeroy and Syracuse, in Ohio and at several points in Mason County, West Virginia. After the salts are removed from the brines the mother liquor, or bittern, is treated with $NaClO_3$ and H_2SO_4 and heated, when bromine is freed and is distilled over into a condenser and caught, or it is separated by electrolytic processes or by treatment with chlorine gas. Much of it is sold in the form of bromides or other salts.

It is used principally in medicines, in photography, in the production of poison gases, as a disinfectant, in chemical laboratories and in the manufacture of tetraethyl lead.

[17] Phalen, W. C., "Technology of Salt Making in the United States," U. S. Bur. of Mines, *Bull.* 146, 1917, pp. 80–94.

The amount of bromine produced in the United States during 1927 was 1,756,310 lbs. valued at $564,689 at the factories. In addition there were imported 486,963 lbs. of bromides valued at $151,612. Before the war the United States was dependent upon Germany for all the bromine it consumed, so that in 1916 the price rose to $5.60 per lb. But during the war necessity forced domestic production of the material, with the result that enough is now produced to meet all needs, and its price has been lowered to about 35 cents per lb.

Most of the bromine of the world is obtained from the bittern from the salt factories at Stassfurt, Germany, in which the bromine content is 15% to 35%. Here the bromine is in bromides associated with the rock salt and other deposits that were precipitated from ocean water (pp. 289–292). In 1925, however, the du Pont Company undertook to separate bromine from ocean water by means of a floating factory with a capacity for treating 7,000 gallons per minute from which between 4 and 5 lbs. of bromine are expected.

CALCIUM CHLORIDE

One of the constituents of salt brine that is often[18] saved is calcium chloride ($CaCl_2$). After the salt and bromine are removed from the brine the remaining bittern is further concentrated and solidified to a mass composed mainly of $CaCl_2$.

It is used to prevent dust on roads, in brine for refrigerator plants, in liquids to prevent freezing and as a drying agent. Its solution is also used in automatic sprinkler systems, to prevent combustion.

Most of the $CaCl_2$ of commerce is made from limestone and common salt, as a by-product in the ammonia-soda process, but in 1927 there were obtained from brines

[18] Phalen, W. C., l. c., pp. 95–97.

95,721 short tons of calcium-magnesium chloride valued at $1,947,797 mainly in California, Michigan, Ohio and West Virginia. Besides 6,514 tons valued at $85,456 were imported.

Nearly all the natural chloride contained notable quantities of magnesium chloride.

SODIUM SULPHATE

Sodium sulphate, or salt-cake (Na_2SO_4), and Glauber's salt ($Na_2SO_4.10H_2O$), or mirabilite, are made in large quantities in the manufacture of hydrochloric acid from rock salt. Niter cake (a mixture of salts, mainly Na_2SO_4 and $Na_2S_2O_7$) is made in the preparation of nitric acid from sodium nitrate.

Salt-cake is used in making plate glass, window and bottle glass, wood pulp and a few other commodities. The hydrated salt is used in dyeing and tanning, in the textile and paper industry and in medicine. Niter cake is used in making fertilizers, in absorbing ammonia and in metal pickling.

In many of the lakes in Arizona, Wyoming, California, New Mexico, Utah, Oregon, Washington and Nevada, sodium sulphate (see pp. 234–236) is an important constituent, which forms in the soil around the lakes efflorescences known as white alkali and in the deeper depressions in former lake basins distinct beds interstratified with layers of epsomite ($MgSO_4.7H_2O$), natrona ($Na_2CO_3.H_2O$) and rock salt. The white alkali is mainly Glauber's salt, or mirabilite, which precipitates at low temperatures, if sodium chloride is not present in large quantity. At higher temperatures or with higher concentrations of sodium chloride the anhydrous form, thenardite, precipitates.

In Sevier Lake, Utah, the deposit in the center of the depression has the composition shown in line I. At

Humboldt Lake the incrustations on the lake borders have the composition indicated in line II.

	Na_2SO_4	Na_2CO_3	$NaHCO_3$	NaCl	H_2O	$Na_2B_4O_7$
I.....	84.6	.4	11.13	7.0	8.0	....
II.....	49.67	7.02	....	20.88	...	11.30

Exposure in dry air causes the Glauber's salt to change to thenardite (Na_2SO_4).

The natural salt separated from lake and playa brines at Camp Verde, Arizona, at Gill Lakes, Wyoming, near Wabuska, Nevada, at Monse, Washington, and at Soda Lake, California, is collected and purified by washing with cold water or brine and is then dried and sacked. After the crust is harvested, the ponds are flooded with enough water to dissolve the efflorescences around their margins and allowed to evaporate for a few weeks after which a new crust forms. The natural salt is consumed west of the Mississippi River as it cannot compete with manufactured salt-cake east of this boundary because of unfavorable freight rates.[19]

Sodium sulphates are known to occur in and around lakes and playas in Saskatchewan, Canada, near Zacatecas, Mexico, at the Karabugus Gulf and at many other points in Asia, in Rumania, Spain and Russia, and solid deposits of the same substances are being worked in Spain, Italy and Saskatchewan.

The amount of sodium sulphate known to exist in the brines in the western parts of the United States and Canada is very great.

The annual production of salt-cake and other forms of anhydrous sodium sulphate in the United States is about 475,000 tons valued at about $3,000,000 and of Glauber's

[19] Wells, R. C., "Sodium Sulphate: Its Sources and Uses," U. S. Geol. Sur., *Bull.* 717, 1923.

salt about 50,000 tons valued at $730,000. Of this amount in 1927 only 23,080 tons, valued at $168,882 were from natural sources. The imports are valued at $11,319, mainly from Saskatchewan, Canada, and the exports, mainly to Canada, were valued at $742,500.

SODIUM CARBONATE

Sodium carbonate, natural soda, or soda-ash, occurs abundantly in the waters of certain lakes in desert regions (see pp. 236–240) and in efflorescences around their borders. It is extracted from the water of Owens and Searles lakes in California,[20] but at present most of the soda-ash of commerce is manufactured.

The water of Owens Lake, at a time when its salinity was 77.098 grams per liter, yielded a residue with the composition shown below.

TABLE XLVII.—ANALYSIS OF THE ANHYDROUS RESIDUE OF THE WATER OF OWENS LAKE

Na_2CO_3	$NaHCO_3$	Na_2SO_4	NaCl	$Na_2B_4O_7$	KCl	SiO_2	Other Salts, Etc.
34.95	7.40	14.38	38.16	.63	4.07	.28	.13 = 100.00

Its efflorescences, like those around other soda lakes, are mixtures of the carbonates, bicarbonates, chloride, sulphates and in some places sodium nitrate and borax.

In 1927 the production of the natural carbonate in the United States amounted to 67,240 short tons, with a value of $1,253,352, and in Canada to 317 tons, valued at $3,170.

[20] Chatard, T. M., "Natural Soda: Its Occurrence and Utilization," U. S. Geol. Sur., *Bull.* 60, 1890.

BORAX AND BORON COMPOUNDS

Until comparatively recently borax was obtained in the United States only from the waters of certain lakes in California and in the Great Basin and from playa deposits in the same general district (Fig. 91).

Later it was made from the minerals colemanite ($Ca_2B_6O_{11}.5H_2O$) and ulexite ($NaCaB_5O_9.8H_2O$), and in the past few years has been mined directly from a deposit of kernite, or rasorite recently discovered near Kramer, Kern County, California. Enormous quantities of borax still exist in the lakes and playas of the Great Basin, but at most places it cannot be extracted at a cost which will enable it to compete in the market with rasorite and with borax made from colemanite. At Searles Lake it is separated on a large scale with profit only because potash salts are separated at the same time.

Colemanite.—Colemanite occurs in Death Valley, and near Daggen in San Bernardino County, and at various points in Ventura, Kern and Los Angeles counties in California, in Clarke County, Nevada, and at several other places in the far west in small quantities.[21]

The colemanite in Ventura County is described by Gale[22] as occurring with layers of intercalated basalt flows and lenses of shale and limestone in the folded and faulted Tertiary lake beds at the south end of San Joaquin Valley.

The colemanite is in crystalline masses of irregular size and shape distributed through the limestone and shale in series of lumps that follow more or less definitely the bedding of the sediments. Gypsum is associated with the borate and occurs as veins in the shales.

[21] Map of occurrences in *U. S. Geol. Sur., Min. Res., 1916*, Pt. II, p. 389, 1918.

[22] Gale, H. S., "Borate Deposits in Ventura Co., Calif.," U. S. Geol. Sur., *Bull.* 540, pp. 432–456, 1914, and p. 85.

FIG. 91.—View of Silver Peak Marsh, Nev. A typical playa. (*Photo by F. R. Porter, U. S. Geol. Sur., Bull. 669.*)

In places limestone nuclei are surrounded by colemanite and tiny veins of the mineral enter cracks in the limestone. Since the gypsum is not of the kind deposited by desiccation of lake waters and there are no other minerals associated with the colemanite that are of the types common to desiccated lake beds it is evident that the colemanite is not a lake deposit. This conclusion seems all the more reasonable since one part of colemanite requires 1,100 parts of water for its solution and all the sedimentary deposits associated with the colemanite were made in shallow lakes. Gale concludes that the colemanite has resulted by the replacement of the CO_3 of limestone by boric acid furnished by emanations from the basalt.

Foshag,[23] however, after a study of several of the known localities has suggested that the mineral has been derived from ulexite ($NaCaB_5O_9.8H_2O$). This mineral occurs as white fibers in groups (cotton balls) in the salt crusts of playa lakes and in the muds below them. Foshag notes that in the presence of NaCl ulexite breaks down into borax and colemanite. His theory is that boron was furnished to the lakes by magmatic solutions emanating from lavas, since no boron compounds are found in lakes distant from igneous rocks. If NaCl and calcium compounds are in the lake water, borax will be formed and in the presence of an excess of NaCl this will cause the precipitation of ulexite. The deposits of such a lake will contain a mixture of borax and ulexite, and as long as borax is present the ulexite will remain unchanged. When, however, the deposits are covered and uplifted the borax dissolves and if the water that traverses the beds contains NaCl the ulexite changes to the insoluble colemanite.

Noble, who describes deposits of the mineral near

[23] Foshag, W. F., "The Origin of the Colemanite Deposits of California," *Econ. Geol.*, Vol. 16, pp. 199–214, 1921.

Kramer[24] and Shoshone,[25] California, reaches a similar conclusion as to their origin in these places. The deposits are associated with tilted and faulted shales, sandstones and lavas covered by alluvial debris. Near Kramer the colemanite and some ulexite occur as lumps in a shale believed to have been laid down by a Tertiary lake (probably in upper Miocene time) and which immediately overlies a great sheet of basaltic lava. Near Shoshone the deposits are of the same kind, but the shale in which they occur is interstratified with tuffs, volcanic ash, sandstone and conglomerate. Here the colemanite bed has an average thickness of 20 feet and at its top in some places is a layer of ulexite 2 feet thick. The ulexite occurs in masses that are similar in form to the masses of colemanite, and many of them have a solid core of colemanite, or have in them crystals of this substance disposed radially.

Kernite, or *Rasorite*.[25a]—Kernite ($Na_2B_4O_7.4H_2O$) is a new mineral which differs from borax in its content of water. It occurs near Kramer, about 25 miles east of Mojave in Kern County, California, as a bed 80 feet thick, underlying a 60-foot stratum of shale carrying colemanite and ulexite. It has already been proven to extend over an area of 40 acres. The mineral is now being mined and some of it has been exported. It is nearly pure, and, as it differs but little from borax, it can be used for the same purposes as this mineral, without the expense of separating it from large amounts of objectionable impurities.

USES

The principal compounds of boron used are borax, $Na_2B_4O_7.10H_2O$, and boric, or boracic acid, $B(OH)_3$.

[24] Noble, L. F., "Borate Deposits in the Kramer District, Kern County, California," U. S. Geol. Sur., *Bull.* 785, pp. 45–61, 1926.

[25] Noble, L. F., "Note on a Colemanite Deposit Near Shoshone, Calif., with a Sketch of the Geology of a Part of Amongosa Valley," *Ibid.*, pp. 63–73.

[25a] *Mineral Industry*, Vol. XXXV, p. 91, 1926.

Boron compounds are used mainly in the manufacture of enamels for iron ware, as flux in the refining of the precious metals, in decomposing chromites, in making glass, preservatives and antiseptics, in tanning leather, as a bleacher, as a mordant, as a cleansing agent, and in toilet preparations. Quite a large quantity of borax is also employed in chemical laboratories. Chromium borate is a green pigment.

OCCURRENCE

The most important occurrence of borax brine is Searles Lake (p. 245), California, on which there are several plants separating borax from brines reached by wells in the bottom of the lake. Other boron-bearing brines are in Borax Lake and Rhodes Marsh (Fig. 92).

The largest colemanite deposits are at Ryan and Shoshone in Inyo County and at Kramer in Kern County, California. Other occurrences are in Los Angeles, Ventura and San Bernardino counties and in adjacent parts of Nevada. Those in Inyo County were worked until the discovery of kernite near Amargo.

The occurrence of kernite has already been described.

PRODUCTION

United States.—All the boron compounds now being produced in the United States come from California and Nevada. In 1927 the quantity obtained was 112,020 short tons valued at $4,348,520.

In the manufacture of borax from colemanite this mineral is treated with sodium carbonate, forming the soluble borax which is crystallized from the solution.

Imports and exports.—The imports of boron compounds were about 7,850 tons of calcium and other borates valued at $231,366 and 67.5 tons of boracic acid valued at $8,222.

Exports in 1927 were 36,954 tons of borax valued at $2,422,144 and about 385 tons of boric acid valued at about $78,000.

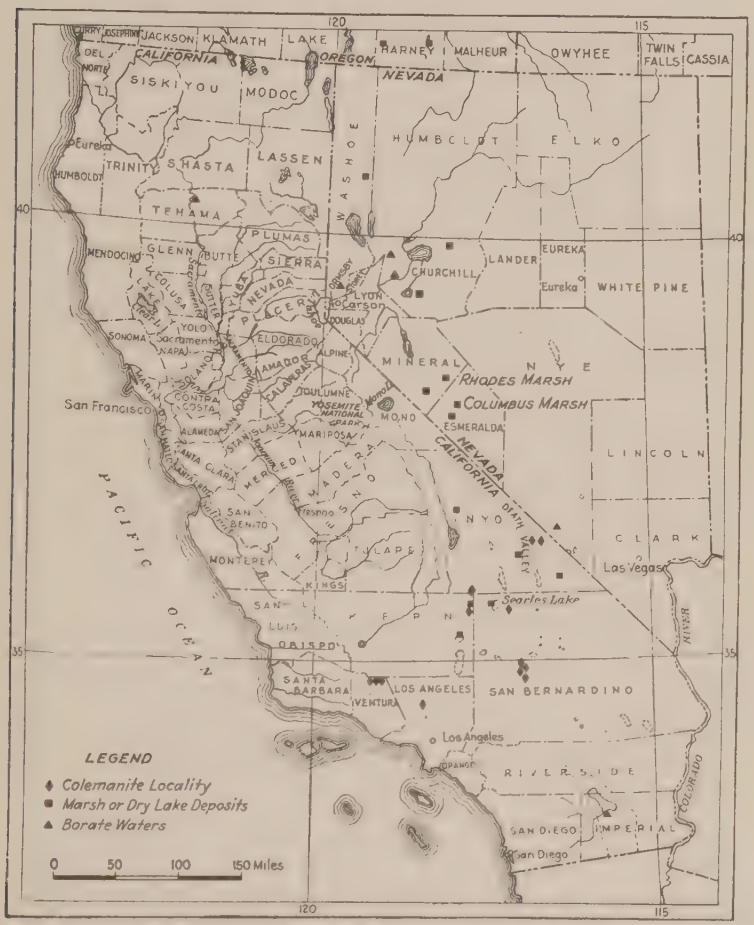


FIG. 92.—Map showing positions of borax deposits in the Western United States. (*After Gale, U. S. Geol. Sur., Min. Res., 1914.*)

WORLD.—Besides the United States the principal producers of boron salts are: Chile, Peru, Argentina, Italy, Germany and Thibet.

TABLE XLVIII.—WORLD'S PRODUCTION OF BORON COMPOUNDS DURING 1926

	Metric Tons
United States	103,545
Chile	27,580
Italy	3,596
Argentina	1,074
Peru	523

In Chile and the neighboring portions of Argentina, Bolivia and Peru are deposits of boro-natro-calcite in playas, into which it has been carried in solution. The playas are in the proximity of old volcanoes, which in Chile and Peru are on the western slopes of the Andes.

In Argentina the crude ore is ulexite.

In Germany boron minerals occur in the Stassfurt salt deposits and in Italy they form deposits in the hot springs and around the fumaroles in Tuscany. (See p. 251.) Turkey has for many years been working a stratum of pandermite ($2CaO.3B_2O_3.3H_2O$) underlying gypsum on the Asiatic side of Marmora, and tincal (borax) has been separated from the muds around lakes in Thibet.

Most of the boron produced in Italy is in the form of boric acid. The natural steam from "steam wells" is passed through water which extracts the boric acid. This weak solution is then evaporated until the acid crystallizes.

POTASH

Potassium occurs in the mother liquor of ocean water but it is rarely deposited from it by evaporation. However, at Stassfurt and a few other places, notably near Mühlhausen in Alsace, at Kalusz in Galicia, in a district between Abyssinia and Eritrea, and in the Province of Barcelona in Spain great deposits of potash salts that are believed to have been deposited from sea water are associated with rock salt, and smaller deposits are known to

exist elsewhere. These furnish the greater part of the potash salts used in the world.

Potash salts occur also in artificial and natural brines pumped by salt makers, in the water of some lakes and in the brines in old lake basins in arid regions. Most of the salt brines, however, contain so little potash that they are not profitable to work. Those buried in dry lakes are being worked at present in this country.

A large quantity of potassium nitrate occurs in Chile, but this is used for special purposes and is not in competition with the deposits of potassium salts deposited from water.

There are also other sources of potassium compounds that are not directly or indirectly connected with solutions, and some of these may become important in the near future.

INORGANIC SOURCES

Brines.—The sources of potash that first come to mind are the deposits in old lake bottoms, the brines of modern lakes, connate brines in porous rocks and those saturating the muds of playas (Fig. 92). All these sources have furnished potash salts in greater or less quantity, but the cost of producing them is so great that competition with the salts obtained from the deposits at Stassfurt cannot be met. At present (1927) only two plants in the United States are obtaining potash from natural brines, both in California. One of them is producing it as a by-product in the preparation of borax from the brine at Searles Lake, and the other as a by-product in the manufacture of magnesium chloride.

In 1927, there were produced from natural brines at Trona, on Searles Lake, in California, about 67,000 tons of crude salts containing about 40,000 tons of available K_2O, valued at about $1,960,000 or 48 cents per unit of

20 lbs. of K_2O, and investigations were being carried on with the view to utilizing for the production of potash the brines near the Great Salt Lake in Utah, those of lakes in that portion of California in the Great Basin, and brines from wells in northwestern Texas.[26]

The Nebraska lakes that furnished 54% of the available potash produced in 1918 have been abandoned completely. (See pp. 241–243.)

Other inorganic sources.—The only inorganic sources of potash in the United States besides brines [27] are alunite, certain shales, sericite schists, feldspar, glauconite and a few leucite rocks. Sylvite has been found in a salt dome near Markham, Texas, carnallite and sylvite in the core of an oil well near Thompsons, Utah, and sylvite, kainite, langbeinite and polyhalite in drill cores from Permian strata in western Texas. These indicate the presence at these places of buried beds of potassium salts, like those at Stassfurt, but the size of the deposits is not known.[28] Recently layers of polyhalite and beds of sediments saturated with potassium-bearing brines have also been found by drilling in southeastern New Mexico.

During the most prosperous period in the potash industry, in 1918, 2,621 tons of available K_2O was made from alunite, 1,549 tons from cement dust and 300 tons from blast furnace dust. Since the close of the war the production of potash salts from these sources has rapidly declined until in 1925 it had practically ceased, although a small production was reported from both furnace dust and alunite in 1926. However, these are sources that may

[26] Hoots, H. W., "Geology of a Part of Western Texas and Southeastern New Mexico, with Special Reference to Salt and Potash," U. S. Geol. Sur., *Bull.* 780, pp. 33–126, 1926.

[27] For a discussion of the potash resources in the brines of the United States see, Turrentine, J. W., "The Occurrence of Potassium Salts in the Salines of the United States," Bureau of Soils, *Bull.* 94, 1913.

[28] Lang, W. B., "Potash Investigations in 1924," U. S. Geol. Sur., *Bull.* 785, pp. 29–43, 1926.

be of importance to America in the future, especially if this continent should be shut off from Europe by the closing of ocean routes.

Alunite.—Alunite $(Al(OH)_2)_6(K_2(SO_4))_4$ is known to occur as veins or dikes at a number of localities in Utah,[29] California and Arizona and an alunitized granite in the San Cristóbal quadrangle in Colorado.

Many of the veins consist of pure alunite while others are composed of a mixture of this mineral and quartz. The crude alunite contains about 37% Al_2O_3 and 10% K_2O. It was probably produced partly in open fissures and partly by replacement of wall rocks by means of hot solutions and gases emanating from igneous magmas beneath.

Very little potash is being made from alunite at present, but in 1918 and several succeeding years, the dike at Marysvale, Utah, was mined on a fairly large scale as a source of potash and aluminum. The material was calcined and leached, producing K_2SO_4 and alum, or it was shipped raw or calcined for use in making fertilizers.

The total amount of alunite in this dike to a depth of 1,000 feet was estimated to be 4,750,000 tons of which 475,000 tons are K_2O. As Al_2O_3 is a by-product in the transformation of the alunite to K_2SO_4, the value of the aluminum made from it helped to bear the cost of extracting the potash. In spite of this, however, the venture ceased to pay when the price of potash salts was reduced after the war. There is, however, known to exist in the Rocky Mountain States a large quantity of alunite that may become a source of potash salts when the need for domestic sources becomes pressing.

[29] Butler, B. S. and Gale, H. S., "Alunite—A Newly Discovered Deposit near Marysvale, Utah," U. S. Geol. Sur., *Bull.* 511, 1912, and
Loughlin, G. F., "Recent Alunite Developments Near Marysvale and Beaver, Utah," U. S. Geol. Sur., *Bull.* 620, pp. 237-270, 1916.

Silicates.—The most abundant potential inorganic sources of potash are silicate minerals and rocks. At present no cheap method of extraction of their potassium components has been invented so that no production from these sources has been accomplished. The most promising of these sources are: the greensands [30] of New Jersey which carry about 7% of K_2O, the feldspar in the pegmatites of the Appalachian region which contains from 7 to 8% of K_2O, the leucite rocks of the Leucite Hills[31] in Wyoming that contain 10% of K_2O, aggregating 197,000,000 tons of K_2O, the sericite slates of Northwestern Georgia[32] containing 10% of K_2O and the Decorah (Ordovician) shales in Minnesota [33] with 6 to 8% of K_2O.

Additional sources [34] of potash are the tailings of copper and gold mines, carrying about 7% of K_2O and aggregating at least 7,000,000 tons of K_2O.

Although it is possible to obtain potash salts directly from all of these potash-bearing silicates the cost of so doing is at present prohibitive,[35] except perhaps in the case of greensand, which by a newly perfected process of extraction yields as by-products alumina and a colloidal silica (glaucosil) which may be employed as an adsorbent. Recent studies indicate that in 10 selected areas in New

[30] Ashley, G. H., "Notes on the Greensand Deposits of the Eastern United States," U. S. Geol. Sur., *Bull.* 660, pp. 27–49, 1918, and

Turrentine, J. W., Whittaker, C. W., and Fox, E. J., "Potash from Greensand (Glauconite)," *Ind. and Eng. Chem.*, Vol. 17, p. 1177, 1925, and

Mansfield, G. R., "Potash in the Greensand of New Jersey," U. S. Geol. Sur., *Bull.* 727, 1922.

[31] Schultz, A. R., and Cross, W., "Potash-bearing Rocks of the Leucite-Hills, Sweetwater County, Wyo.," U. S. Geol. Sur., *Bull.* 512, 1912.

[32] McCallie, S. W., "High Potash-bearing Slates in Georgia," *Eng. and Min. Jour.*, Vol. 104, p. 643, 1917.

[33] Schmitt, H. A., "Possible Potash Production from Minnesota Shale," *Econ. Geol.*, Vol. 19, pp. 72–83, 1924.

[34] Butler, B. S., "Potash in Certain Copper and Gold Ores," U. S. Geol. Sur., *Bull.* 620, pp. 227–236, 1916.

[35] For a discussion of the available supplies of potash, see U. S. Geol. Sur., *Min. Res., 1917*, Pt. II, p. 397.

Jersey, there is greensand enough to furnish 67,900,000 tons of K_2O, but at present there is no commercial production from this source, because of the difficulty in marketing the by-products.[36]

Some of the other materials mentioned are, however, furnishing potash as a by-product. The raw materials of many blast furnaces and cement plants contain potash-bearing substances, such as feldspar and shales, from which the potash is driven by the high heat to which they are subjected. The potash is volatilized and is collected in the flue dust.

Blast furnace dust separates from the gases that pass up the flues. It contains much of the volatile constituents of the burden. Where the ore contains much orthoclase the dust often contains from 6% to 9% of K_2O. Most of this is sold without treatment, but some is leached, producing K_2SO_4. Six furnaces produced potash in 1924 and five in 1925, but the quantity saved was small. The present estimates of the recoverable potash from all the blast furnaces in the United States range from 50,000 to 200,000 tons of K_2O annually.

Cement mills promise the largest production of potash, if some method can be evolved which will lower the cost of separating the potash from objectionable ingredients in the dust. Only one mill reported recovery of potash cement dust during 1924. This abandoned the practice in 1925. In 1918 twelve mills saved their dust and made over 12,000 tons of crude salts containing 1,550 tons of available K_2O. The recoverable potash in all the cement dust produced in the United States annually is believed to be 75,000 tons.

It is estimated [37] that if all the potash now lost annually

[36] Thoenan, J. R., "Potash from New Jersey Greensand," *Reports of Investigation*—U. S. Bureau of Mines. Serial No. 2910. Feb., 1929.

[37] Turrentine, J. W., *Potash—A Review, Estimate and Forecast.* New York, 1926.

in blast furnace and cement dust were saved it would amount to 80% of our importations of potash salts.

ORGANIC SOURCES

Organic sources of potassium compounds are of more immediate interest than are the inorganic sources aside from the brines and the bedded salt deposits.

Wood ashes and kelp.—Wood ashes were the main sources of potash of nearly all countries in early times. In the early days of this country they were the only source of the alkalies employed in soap making, but with the decrease in the forests the quantity of wood ashes produced has fallen off until now the production has practically ceased as a source of potash. In 1918 about 670 tons of available K_2O is credited to wood ashes but in 1924 none was reported.

Kelp has also furnished small quantities of potash from very early times. In 1918, it yielded 4,804 tons of available K_2O, but since that year the production has diminished until in 1920 it ceased. Steps have recently been taken to organize a company to cut kelp on the Pacific coast and extract from it potash, iodine and ammonium sulphate. If the company succeeds there will be a small but constant supply of potash from this source.

Distillery waste and Steffens water.—The two most promising sources of potash are by-products of large industries, and consequently are sources that can be relied upon to furnish a continuous supply of the commodity.

Molasses distillery waste and Steffens waste water from beet sugar factories contain sufficient potash to warrant an attempt to save it. In 1924 about 15% of the entire production of potash (3,430 tons) in the United States was from distillery waste and .3% or 72 tons was from Steffens water.

Distillery waste is derived from molasses that has

fermented and been distilled in the manufacture of industrial alcohol. This is concentrated and dried, yielding a potash residue consisting of a mixture of chloride, sulphate and carbonate that is used for fertilizer. Estimates place the amount of potash that could be saved from distillery waste at about 35,000 tons. At Baltimore a million gallons of waste are (in 1927) treated daily, yielding about 1,800 tons of commercial potash salts monthly and a large quantity of ammonium sulphate. The mixture of potassium salts marketed in 1925 contained 33% of K_2O.

Steffens water is the waste after treating beet molasses for sugar. It is a very dilute solution of the salts that occur in beets. It is evaporated until the concentrated solution contains about 11% of K_2O and is put on the market in this form or is dried and charred. The potash char contains from 32% to 42% of K_2O. In 1918 the amount of K_2O produced from this source was 1,374 tons, but the cost of concentrating the dilute liquor is so great that only 72 tons were made in 1924. It is estimated that the amount of potash wasted in Steffens water in the United States is about 8,000 tons annually.

USES

Before the war the United States imported 1,092,588 tons of potash salts containing 270,720 tons of K_2O. The salts imported included kainite ($MgSO_4.KCl.3H_2O$), carnallite ($KMgCl_3.6H_2O$), fertilizer salts, sylvite (KCl), and 8 or 10 other less important compounds. Most of them were used in making fertilizers. During this period the country depended entirely upon Germany to supply its demands. During the war, however, when trade with Germany was interrupted the domestic resources began to be developed and in 1918 about 22% of the normal consumption was produced, or an aggregate of 192,587 tons of salts containing 52,135 tons of available K_2O.

The principal needs for potash are in agriculture and in the chemical industries. It is estimated that a crop of 250,000,000 bushels of wheat removes from the soil about 100,000 tons of potash (K_2O). Cotton, tobacco, potatoes and truck farm products remove a still larger amount. This must be replenished. The chemical industries consume about 10% of that used in fertilizers. In 1923 the consumption of crude potassium salts was 730,000 tons containing 222,000 tons of K_2O. Of this the United States produced crude salts containing 10% of the total K_2O, representing 6% of the total value. The rest was imported.

PRODUCTION, IMPORTS AND EXPORTS

UNITED STATES.—Of the 22,896 short tons of available potash manufactured in the United States during 1924, California produced 19,361 tons, Maryland 3,430 tons and Indiana and Pennsylvania together 105 tons. The product was valued at $842,618 and was used in fertilizers. In 1927 the production of crude salts was 76,819 short tons containing 43,510 tons of available potash, and the sales were 94,722 tons valued at about $2,448,146. The largest production was from the brine of Searles Lake, in California, where 67,000 tons of nearly pure potassium chloride were produced, and from molasses distillery waste at Baltimore, Maryland, where 11,000 tons of crude salts containing 33% of K_2O were made. Smaller quantities of potassium compounds were separated from Steffens waste in Michigan, from blast furnace dust at Pittsburgh, Pennsylvania, and from glauconite, at Odessa, Delaware. Some alunite was shipped from Marysvale, Utah, for experimental purposes.

In 1925 there were imported compounds containing 258,217 short tons of K_2O of which 239,167 tons valued at $12,730,019 were used in manufacturing fertilizers and 19,050 tons valued at $4,641,747, were used in making

chemicals. The total imports of potassium compounds in 1927 were 730,597 tons containing 224,973 tons of K_2O, and valued at $18,369,825, of which by far the greater part was used in making fertilizers.

The exports in 1927 were 1,965 tons of salts valued at $487,726.

Of the imports in 1927 the greatest value ($11,005,425) came from Germany. France furnished salts valued at $2,264,458 and Belgium salts valued at $2,942,900. The principal compounds imported were crude kainite (KCl. $MgSO_4.3H_2O$) with a guaranty of a minimum potash content of 12.4%, manure salts, a mixture of KCl, NaCl and $MgSO_4$, with a guaranteed content of over 20% K_2O, muriate, a mixture of KCl and NaCl, with a minimum content of 50% of K_2O, and sulphate (K_2SO_4), with a guaranteed content of 48.6% K_2O. The other potassium imports were of manufactured salts. The muriate and sulphate, while used principally as fertilizers, are also the crude materials from which refined potassium salts are made.

The outputs for 1927 are shown below in metric tons:

TABLE XLIX.—WORLD'S PRODUCTION OF POTASH SALTS IN 1927

(In metric tons)

	Crude Salts	K_2O *Content*
Germany	11,071,541	1,518,037
France	2,231,775	372,049
Poland	277,093	43,825
United States	69,689	39,471
Spain	81,548	12,000± (a)
Italy:		
Alunite	800	(b)
Leucite rock	56,000	4,500
Others	6,000±	(a)

(a) In 1926 (b) Data not available.

World.—Nearly all the potassium salts that enter the world's markets come from Germany and France, but increasing quantities are being contributed by Spain and Poland.

OCCURRENCES

The principal deposits of potassium salts now being worked are in Germany and France, but many other deposits are known to exist elsewhere, and some of these may soon become of importance.

United States.—The only occurrences of potash in the United States that can be depended upon to supply this country's needs are the brines of old lakes in the arid and semi-arid regions of the southwest,[38] the mineral alunite, the feldspars in ores and cement mixtures, and the organic substances that are used mainly in the production of sugar and alcohol (Fig. 93). There seems no prospect that all of these together will furnish enough potash to meet the country's demands, although recent drilling in the Permian salt basin of western Texas and southeastern New Mexico has revealed the presence in some places of polyhalite beds thick enough and rich enough to suggest commercial exploitation.[39] It is probable however that the greater part of the country's supplies must be drawn from outside sources.

Another possible source of potash salts is in the salt domes of Texas and Louisiana. It is known that potash minerals occur in some salt domes elsewhere, and that in at least one salt dome in Texas there is some sylvite, but no potash has ever been discovered in the salt mines of Louisiana, and no traces of potash minerals have been

[38] Nolan, Thos. B., "Potash Brines in the Great Salt Lake Desert, Utah," U. S. Geol. Sur., *Bull.* 795, pp. 25–44, 1928.

[39] Mansfield, G. R. and Lang, W. B., "Government Potash Exploration in Texas and New Mexico," Am. Inst. Min. and Met. Engrs., *Tech. Publications*, No. 212, 1929.

found in the fairly numerous cores of salt that have been taken from domes in drilling oil wells, except in the one case referred to, and, consequently, it is concluded that the chances are not favorable for the existence of commercial bodies of potash salts in these domes in either of the two States named.

GERMANY.—Germany contains by far the largest known segregation of potash salts in the world. Beds of rock salt,

FIG. 93.—Map of United States showing the location of the principal natural sources of potash. (*After Mansfield and Boardman, U. S. Geol. Sur., Min. Res., 1923, Pt. II.*)

which are of Permian age, occupy an enormous basin in the plains of central Germany and extensive deposits of potash salts occur in their upper layers in certain localities, notably in the vicinity of Stassfurt (Fig. 94). In 1910 the Geological Institute of Berlin estimated that the potash deposits occupy a volume of 10,790,000,000 cubic meters and contain about 20,000,000,000 metric tons of potash salts corresponding to about 2,000,000,000 metric tons of potash (K_2O), a quantity sufficient to supply the world for 2,000 years at the present rate of consumption. The

chief potash salts in the deposit are carnallite, kainite, and sylvite. The potash-producing companies all belong to the Kali Syndicate, which under the supervision of the

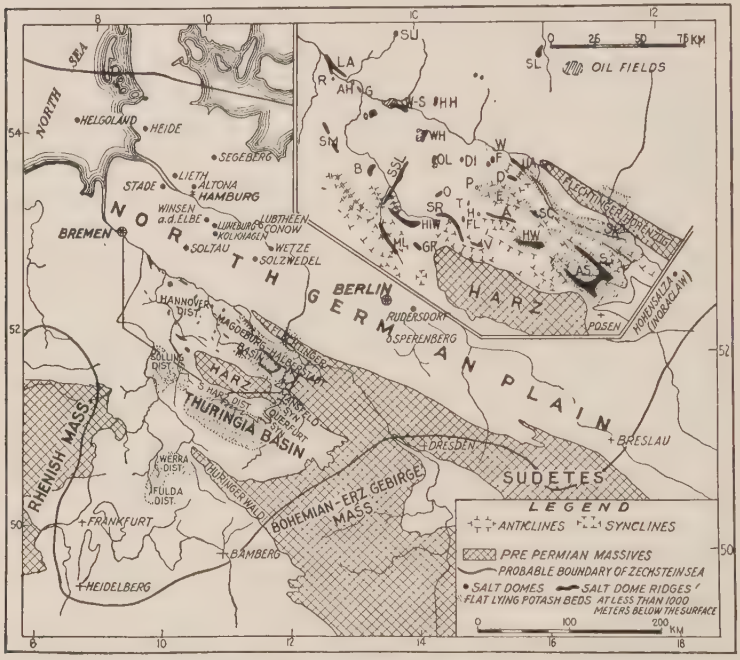


FIG. 94.—Map of the North German salt deposits showing the occurrence of the salt domes and ridges, the potash within minable depth, and the salt dome oil fields. All of the salt domes are or are supposed to be potash bearing, although no potash is mined at the present time from some of the domes out in the North German Plain. (*After Everding, Einecke, Seidl, Stille, Lepsius, and Fulda.*) (*Adapted from map by D. C. Barton, University of Texas, Bulletin 2801.*)

German Government determines the production of each mine, distributes the product, and regulates the prices.

The Stassfurt deposits consist of the series of beds listed.

The Carnallite zone furnishes all the commercial potash coming from the Stassfurt deposits.

TABLE L.—VERTICAL SECTION OF THE SALT DEPOSIT AT STASSFURT, GERMANY

Zone	*Description of Beds*	*Thickness*	*Depth from Surface*
		Feet	Feet
Overlying main Salt deposit	440 feet of red and blue clay slates; 80–100 feet of practically pure rock salt; 133–300 feet of anhydrite ($CaSO_4$); 20–30 feet of saline clay.	840	840
Carnallite	This zone consists of about 55% of carnallite ($KCl.MgCl_2.6H_2O$), 25% of rock salt (NaCl),16% of kieserite ($MgSO_4.H_2O$), and 4% of various other salts. Sand, clay, etc., kainite, sylvine and other alteration products are prominent in certain places. The average percentage of potash (K_2O) in the zone is 9.27.	140	980
Kieserite	This zone contains about 65% of rock salt, 17% of kieserite, 13% of carnallite, 3% of bischofite ($MgCl_2.6H_2O$), and 2% of anhydrite ($CaSO_4$). The average percentage of potash (K_2O) is 2.17.	187	1,167
Polyhalite	This zone consists of about 91% of rock salt, 6.6% of polyhalite ($2CaSO_4.MgSO_4.K_2SO_4.2H_2O$), 15% of magnesium chloride, 0.7% of anhydrite, and 0.2% of sulphur, bituminous substances, etc. The average percentage of potash (K_2O) is 1.02.	207	1,374
Anhydrite	This zone consists of layers of rock salt about 4 inches thick, separated by beds of anhydrite about ¼ of an inch thick. By mechanical separation rock salt 99% pure is obtained on a large scale. Only traces of potassium are present.	2,000	3,374

In some places these beds are approximately horizontal. In others they are deformed into gentle arches, and in others have been sharply folded into fairly steep anticlines.[40] In some portions of the basin the salt series has been forced upward into the overlying beds producing genuine salt domes in which the salt layers are completely contorted. The salt series has apparently flowed more or less as a whole and has been intruded for many feet into overlying sediments and has lifted them far above the positions they originally occupied (Fig. 95).

Recently another deposit of salts containing potash has been discovered at Buggingen, in Baden, near the border of Alsace, but its importance has not yet been determined.

Before the world war Germany monopolized the trade in potash to such an extent that the German Government was able to dominate the world in the potash industry, but at the close of the war when Alsace was given to France this monopoly was broken and hope was entertained that the world would benefit by the competition between German and French interests, and by the close of 1919 the developments in the Alsace district seemed to indicate that this hope would be realized. In 1924, however, the French and German interests combined, raised the prices on potash salts, and agreed to divide the world's business between them. At present the group possesses 90% of the world market.

In 1927 the total sales of German potash salts aggregated 1,239,395 metric tons of K_2O, valued at about $46,000,000. Only 40 of the 228 available shafts were operated.

France.—In Alsace potash salts were discovered at Wittelsheim, 6 miles northwest of Mülhausen, in upper Alsace, in 1904, while drilling for oil (Fig. 96). Subsequent

[40] Barton, D. C., "The Economic Importance of Salt Domes," Univ. of Texas, *Bull.* 2801, pp. 8–13, July, 1928.

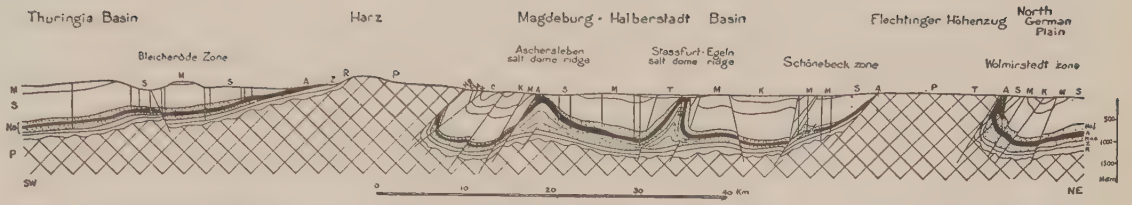


FIG. 95.—General cross-section of the north German potash-bearing salt deposits showing the contrast of the very slightly deformed beds of the Thuringia Basin with the sharply deformed beds of the Magdeburg-Halberstadt Basin. (*After Everding, Geinecke, Schunemann, and Seidl.*) The potash-bearing beds lie in the stippled zone immediately below the broad black band representing the "Main" anhydrite. T=Tertiary, C=Cretaceous, K=Keuper, M=Muschelkalk, S=Buntsandstein, Na=Salt Series (Na-j, the "Younger" Salt Series; A, the "Main" anhydrite; and Na-a, the "Older" Salt Series), R=Rotliegendes, P=Pre-Permian. (*After D. C. Barton: Univ. of Texas Bull. 2801.*)

explorations and developments indicate that the deposits underlie an area of more than 70 square miles, and that the

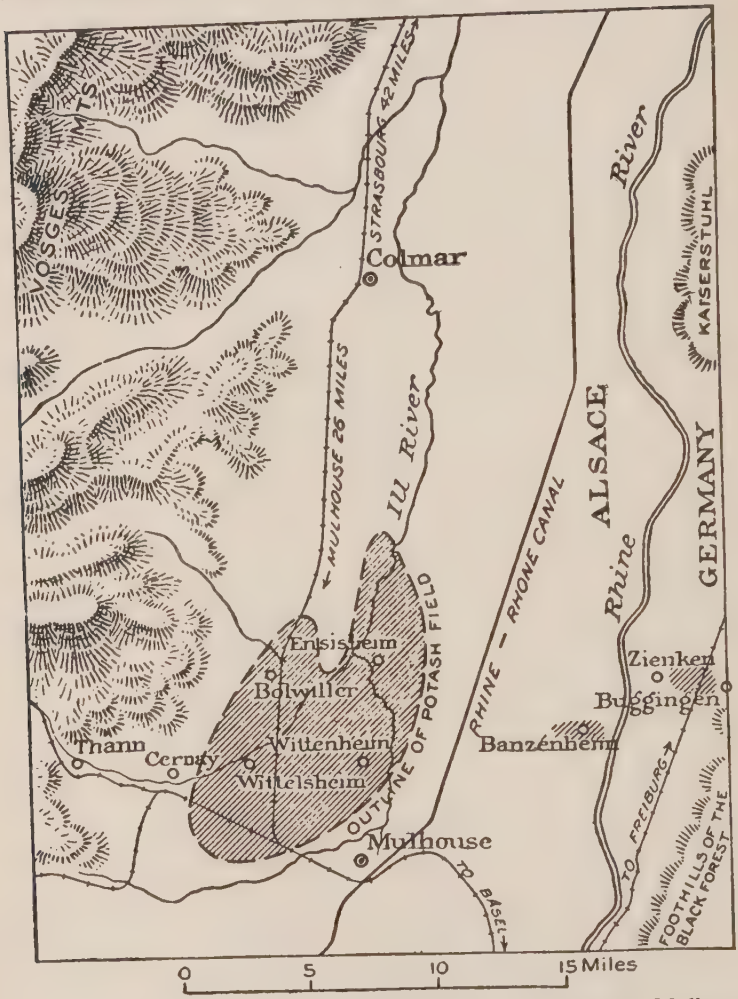


FIG. 96.—Sketch map showing position of salt deposits near Mulhouse, Alsace. (*After Gale, U. S. Geol. Sur., Bull. 715.*)

workable beds have a depth of about 2,000 feet and range in thickness from 6 to 30 feet. The salts consist essentially

of sylvinite, a mixture of sylvite and rock salt. Practically no carnallite or magnesium chloride is present. Estimates place the amount of potash salts in the deposit at 1,472,058,000 tons, which on a basis of 22% of potash (K_2O) gives more than 300,000,000 tons of potash.[41]

By the Treaty of Versailles these mines were transferred to France. In 1925 the Alsatian mines were equipped to produce about 12,000 tons of crude salts daily or over 4,000,000 tons annually. The production of salts in 1924 was 1,230,000 metric tons, and in 1926 about 2,231,755 tons, containing 372,049 tons of K_2O.

Another deposit of salts containing considerable potash has recently been reported from the Pyrenees district in southern France. Here a 90 foot thick layer of salts with 11 to 94% of potassium chloride lies at a depth of 180 to 270 meters. Its extent is not yet known, but the deposit is considered to be workable on a commercial basis.

Spain.—In Spain potash deposits were discovered a few years ago in the Province of Barcelona, Spain, near the villages of Suria and Cardona (Fig. 97). The salts occur in Oligocene (Tertiary) formations. They consist of irregular beds of carnallite and sylvinite interbedded with and occurring in rock salt. The average combined thickness of the carnallite beds is estimated to be about 56 feet, and of the sylvinite about 13 feet. The Cardona deposits occur in the axis of a sharp anticline. The upper beds are interbedded with gypsum and clay, but the lower beds contain nearly pure white salt. After the discovery of potash in Suria, these Cardona beds were searched for potash, and nearly pure sylvite was found. Estimates for the area prospected place the quantity of crude salts at 2,000,000,000 tons.

[41] Gale, H. S., "The Potash Deposits of Alsace," U. S. Geol. Sur., *Bull.* 715, pp. 17–55, 1921.

No production has been reported from this source, but it is stated that the Solvay Company has already made preparation to begin shipments.[42]

ERITREA.—In Eritrea a large deposit of potash salts

FIG. 97.—Sketch map of the salina at Cardona, Spain. (*After Gale, U. S. Geol. Sur., Bull. 715.*)

said to resemble that at Stassfurt, Germany, was discovered in 1911 near the boundary between this country and Abyssinia. It is in a desert about 46 miles inland from the settlement of Fatimari, which is opposite the island of Baca in the Red Sea. In 1914 an Italian organ-

[42] Gale, H. S., "The Potash Deposits in Spain," U. S. Geol. Sur., *Bull.* 715, pp. 1–16, 1921.

ization undertook to develop this property, but, owing to difficulties connected with the management of the operating company, only a few hundred tons of potash have been produced. In 1926 an output of 1,200 tons of potassium chloride is reported. The company estimates at least 850,000 tons of salts high in potash in the deposit.

At present only a superficial deposit formed by the evaporation of the water of hot springs has been worked, but drilling has revealed the existence of extensive buried brines.

Galicia.—In the salt deposits near Kalusz, Galicia, potash salts occur at four different horizons in lenticular beds, which attain a thickness of 20 feet and are interbedded with rock salt and saline clay. They contain kainite and sylvinite, with relatively small quantities of carnallite, and yield an average of about 10% of potash (K_2O). The total amount of the salts in the deposit is estimated at 100,000,000 tons. The production in 1927 was 275,456 metric tons of potash salts of which 127,124 tons were kainite and the rest sylvite. This, however, is not sufficient to supply the Polish demands.

Russia.—Deposits of potash salts and brines containing potash are known to exist in Russia, and some of the occurrences are probably very large. Rich potash brines fill some of the lakes in the Crimea and in Caucasus, and from some of these about 400 tons of potash salts were separated in 1926. In a few years it is expected that the production will be greatly increased.

The most promising deposit is in the Solikamsk district, Province of Perm, where drills have penetrated 39 meters of workable carnallite beds and 12.5 meters of workable sylvinite strata, containing at least 68,000,000 tons of K_2O. Two other deposits, one near Beresniki, on the River Kame and the other on the Soeikamsk are reported to contain more potash than exists in Germany. The total

amount of potash (K_2O) believed to exist in these districts is estimated to be greater than 1,800,000,000 metric tons.

Other occurrences.—The water of the Dead Sea in Palestine is known to contain 251 grams of salts per liter at a depth of 200 meters, and that 3.8% of the total is KCl, or about 10 grams per liter. This is equivalent to 1,300,000,000 tons of KCl. There are also present in the sea 853,000,000 tons of MgBr. It is believed that these salts can be extracted at a cost that will be profitable, when a cheap method of transportation to a shipping point is available.

Small deposits of sylvite have recently been discovered at Malagash, Nova Scotia, and at several places in Saskatchewan, Canada, but they are not likely to be of commercial importance.

In Australia, Japan and Italy are occurrences of alunite that is mined for its potash content.

Japan, also, produces small quantities of potash from kelp, sea water bittern and the ashes of wild banana stalks, and Canada and Sweden recover potash from cement dust, but the contributions of these countries to the potash trade are inconsiderable.

In Italy there are about 200,000 tons of alunite available, but only a small quantity is utilized.

The most promising source of potash in this country, aside from that in dry lake and lagoon deposits, in brines and in playa deposits, is the mineral leucite which occurs abundantly in some volcanic rocks. Within the past few years methods of separating the potash from this silicate have been so successful that plants are now being constructed to use it in the manufacture of potassium nitrate and aluminum.

To complete the record of the world's available potash resources reference should be made to the separation of

potassium nitrate from the soda niter deposits of Chile and from the niter beds in India. These salts, however, are used for special purposes to which the other potash salts are not adapted. It is estimated that the sodium nitrate now produced in Chile contains 150,000 tons of potassium nitrate which may be saved by efficient processes. (See p. 301.)

SODA NITER, OR CHILE SALTPETER

Soda niter, or Chile saltpeter, is sodium nitrate, $NaNO_3$. Though it is found in small quantity around some of the lakes in the Great Basin and particularly in the soil around the shores of the Eocene lake that occupies Death Valley in California,[43] its principal source is the arid portion of Chile east of Iquique,[44] where the climate is rainless (Fig. 98). There the niter forms a bed under a conglomerate, or breccia (costra), and soil 1 foot to 18 feet thick. It may have been formed by the slow oxidation of guano, etc., or by the nitrifying action of bacteria upon organic matter, though many geologists are inclined to believe it was formed in some other way. A few ascribe the production of nitric acid to the oxidation of atmospheric nitrogen by electrical discharges and the existence of the soda-niter to the action of this acid upon sodium-bearing rock minerals. Miller and Singewald explain the deposits as having "resulted from the accumulation, by means of evaporation, of the minute nitrate content of the underground waters of the region." They contend that while the nitrates may have been formed by any one of the processes that have been suggested by the large number of geologists who have studied the deposits, these processes

[43] Gale, H. S., "Nitrate Deposits," U. S. Geol. Sur., *Bull.* 523, 1912.

[44] Singewald, J. T., and Miller, B. L., "The Genesis of the Chilean Nitrate Deposits," *Econ. Geol.*, Vol. 11, pp. 103–114, 1916, and discussion, Vol. 12, pp. 92 and 95, 1917.

FIG. 98.—Sketch showing position of nitrate fields in Chile. (*After Whitehead, Economic Geology, Vol. 15.*)

are also active elsewhere. The outstanding fact, according to them, is that in this district there has been a great accumulation of the salt, and it is this fact and not the method of origin of the nitrate that needs explanation. The deserts of Chile extend from the equator to about 30° S., where the winds blowing from the west toward the Andes Mountains are dry. The nitrate deposits are in playas, or "calicheras." The deposit, known as "caliche," is covered with layers of "costra," a low grade "caliche" mixed with salt, fragments of feldspar and earthy matter having a thickness of 1 foot to 3 feet. Over this is a 2 to 10 foot layer of earth and stones, 6 inches of porous earthy gypsum and on the surface a layer of sand and gravel 1 inch to 2 feet thick.

The "caliche" itself, which is from 1 to 3 feet thick and lies in clay, is a mixture of calcium, sodium, potassium and magnesium sulphates, chlorides and nitrates with some iodates and double salts of nitrates and sulphates. The chemical composition of the mass varies greatly. The insoluble material ranges from 0.30% to 47.34%, the NaCl from 3% to 50%, the $NaNO_3$ from 22% to 62% and the KNO_3 from a trace to 17% or more. Potassium chlorate is also present in small quantities, in some places to as much as 6.70%. Borax, bromides and phosphates also occur in it locally.

Whitehead [45] ascribes the presence of nitrate in the soil to the oxidation during weathering of ammonium salts existing in the Mesozoic tuffs and lavas that underlie much of the nitrate area. It is assumed that the ammonium salts were contributed by volcanic emanations accompanying the formation of the tuffs, and that during the erosion of the tuffs their ammonium contents were oxidized to nitrates, which were concentrated by super-

[45] Whitehead, W. L., "The Chilean Nitrate Deposits," *Econ. Geol.*, Vol. 15, pp. 187–224, 1920.

ficial waters causing slow downward migration from the hillsides on which the tuffs outcrop, during the development of the present desert topography. He asserts that "in one large nitrate field the erosion of one meter of rock carrying 1% NH_4Cl over merely the nitrate bearing parts of the field would satisfy the nitrate content."

The deposits are dug, and leached with water and the solutions thus obtained are evaporated and the crudely crystallized mass is shipped.

Much of the crude salt is later refined to produce pure $NaNO_3$, but large quantities are employed in the manufacture of nitric acid and other large quantities are put into fertilizers. The total production of sodium nitrate in Chile during 1926 was 2,023,000 metric tons, of which 914,298 tons, with a value of $42,781,386, were delivered in the United States. In 1927 the production increased, but it is probable that during the next few years it will tend to diminish, because of the increasing competition of synthetic nitrogenous compounds extracted from the air.

In northern Argentina, in the valley of the San Sabastiano River in Colombia, and at Cochabamba, Bolivia, are other playas in which nitrates occur. In Argentina the playas are covered with rock salt but around their borders are colemanite, priceite, ulexite and other borax minerals. The bittern in the centers of the depression are solutions containing $NaNO_3$. In Colombia the niter is a layer ½ to 3 meters thick underlain by a mixture of gypsum and calcareous clay.

Recently a large deposit of mixed salts containing sodium nitrate has been reported to occur at Matsap, Cape Province, S. Africa.

Soda niter is also known to occur in caves and under shelving cliffs occupied by bats and in the crevices of rocks under bat roosts. It is also abundant in the soil of some

portions of California, Colorado, New Mexico and elsewhere where it was formed by bacterial action, but in none of these places is it in large quantity. Experiments on the soil of Colorado show that in 48 days under favorable conditions the maximum increase in the amount of nitric nitrogen present in this soil was 138%, corresponding to the formation of 5 tons of $NaNO_3$ per acre-foot annually. It is probable that alkali nitrates are being formed at most places, but they are so very soluble that they are washed away by the rains and carried into the ground water, and consequently are prevented from accumulating, except in very dry regions.

Large deposits have been reported as occurring near Winkelman, Ariz., covering an area of 8 square miles and near Glenrock, Wyoming. At both places development work has been started, but no nitrate has as yet been placed on the market.[46]

All of the soda niter used in the United States is imported, and most of it comes from Chile. The average imports are 750,000 short tons valued at $40,000,000. In addition other inorganic nitrogenous compounds imported for use in making fertilizers aggregate about 50,000 tons, valued at $2,600,000. The greater part of these is calcium cyanimid. Ammonium sulphate and calcium nitrate make up the remainder. Since these three compounds are made in ever-increasing amounts from the air, it is prophesied that before long these synthetic products will drive the natural nitrate from much of its present market.

In 1927 the natural and manufactured nitrogenous compounds produced in the world were equivalent to 1,237,500 tons of pure nitrogen. Of this amount the Chilean nitrate supplied only 199,600 tons.

[46] *Eng. and Min. Jour.-Press*, Vol. 120, p. 708, 1925 and Vol. 121, p. 255, 1926.

SALTPETER, OR NITER

Saltpeter, or niter (KNO_3), is used for purposes widely different from those for which other potassium salts are employed. Its value depends only partly upon its potassium content, its main value being due to its nitric acid component, and the fact that it is not hygroscopic.

It is used in the manufacture of black powder and fireworks, as an oxidizing agent, as a preservative of meat, as a chemical reagent, in medicine and in fertilizers, though for fertilizers it is not as popular as soda niter because of its higher cost.

Niter is formed through the action of nitrifying bacteria upon nitrogenous organic matter in the presence of potash. It occurs mainly in caves, in the earth around native villages in warm countries, in the soil of arid regions and in the caliche of the Chilean nitrate fields and in certain playa deposits in South America.

In India the offal from the villages is emptied on the soil near the village site that has been inoculated with nitrifying bacteria. After a little time the soil is scraped up, leached with water and the solution is evaporated yielding an impure salt composed largely of KNO_3. This is bagged and shipped.

In the caves the source of the niter is usually bat guano, which exists in the caves of nearly all States south of the Potomac and Ohio rivers. From many of them niter was obtained during the Civil War. Niter has also been found in the walls of ancient cliff dwellings in Arizona and as incrustations on the under sides of cliffs that once formed the shores of Lake Lahontan, Nevada. An analysis from a deposit at Gerlack gave:

Insol.	NO_3	Na	K	Other Substances
10.04	52.40	1.07	33.61	Small

Similar deposits occur at various points in Utah and Wyoming, under cliffs, in crevices and other protected situations. In all cases the mineral may have been produced by water percolating through bat guano.

The caliche of the Chilean nitrate fields contains from a trace to more than 17% of potassium nitrate which is separated from the caliche as a by-product in the manufacture of sodium nitrate. The process consists in evaporating the mother liquors to a high density and then cooling the concentrated brine, thus causing a product containing about 25% potassium nitrate to be deposited. At present but a small portion of the KNO_3 is being saved, but if all the potash in the caliche were recovered about 150,000 tons would be produced annually.

A playa deposit of niter has been described as occurring at Cochabamba, Bolivia, but very little is known about it. The deposit consists of 60.70% KNO_3, 30.70% $Na_2B_4O_7$ and 8.60% organic matter. If the discovery is substantiated the occurrence is of considerable commercial interest, as the KNO_3 and $Na_2B_4O_7$ are both valuable.

The importation of saltpeter into the United States is about 2,800 short tons annually having a value of $200,000. Nearly all comes from India and Chile. Most of the niter used in this country is made from soda niter by treatment with potassium chloride. In 1918 this amounted to 16,250,433 lbs. valued at $4,400,000.

IODINE

All the iodine that has been produced in the United States was furnished by the kelp that grows in the Pacific Ocean and extracts the element from the sea water which contains about one part of iodine in 250,000 parts of water. Analyses of the ashes of three genera of kelp are shown in the table on the following page.

Table LI.—Analyses of the Ashes of Kelps

	K_2O	I	N	Insol.
58 analyses	12.59	1.57	...	5.9
15 analyses	9.1	Tr.	2.6	7.5
21 analyses	20.1	.13	1.9	4.2

The plants were cut, dried and burned and their ashes were leached. The solution was crystallized and KI was separated, or the iodine set free by reagents and distilled. At the present time no iodine is produced from this source, but in the future it is expected that kelp will again be utilized for the production of the element.

Iodides occur in a few oil-well waters but not in sufficient quantities to be of commercial importance.

The imports of iodine into the United States during 1927 amounted to 926,492 lbs. valued at $2,900,574, all from Chile.

Most of the world's production comes from Chile where iodine occurs in the rare mineral lauterite, $Ca(IO_3)_2$, and in a double salt of $CaIO_3$ and $CaCrO_4$. The iodate is separated in the preparation of niter (KNO_3), but only about 2% of the available iodine in the nitrate is being saved.

Iodine is also obtained in small quantities from algæ and other marine plants, notably in Scotland, Normandy, Norway and Japan, and from well water in Java.

The total production of iodine in the world during 1925 was about 970 metric tons, of which Chile contributed 786, Japan 61, France 55, Java 38, Great Britain 25 and Norway 5.

CHAPTER IX

GYPSUM AND ANHYDRITE

ORIGIN

Gypsum ($CaSO_4.2H_2O$) has been repeatedly referred to as a deposit associated with halite in beds formed by the evaporation of sea water. It precipitates before the halite and consequently is formed beneath it. Usually, however, there is a recurrence of the conditions of precipitation and we find the salt and gypsum interbedded. Since, however, calcium sulphate separates from sea water above 25° as anhydrite instead of gypsum, it often happens that anhydrite and gypsum occur together. The anhydrite is harder than gypsum and is objectionable for most purposes on that account. Moreover, it is already anhydrous and cannot therefore be calcined for plaster-of-Paris. It is, therefore, regarded as an impurity in gypsum that is mined for any use other than as a fertilizer, or for the manufacture of sulphuric acid and ammonium sulphate.

Since anhydrite and gypsum in many deposits are irregularly intermixed and in many others the anhydrite underlies the gypsum, it has been thought by some geologists that anhydrite in commercial deposits was the original deposit and that gypsum has been produced by its hydration.[1]

It rarely happens that salt deposits are unassociated with gypsum or anhydrite. It frequently happens, however, that beds of these sulphates are found without

[1] Wilder, Frank A., "Gypsum and Anhydrite," *The Amer. Min.*, Vol. 13, pp. 476–480, 1928.

salt (Fig. 99). This may be accounted for by the fact that after the sulphate was precipitated an end was put to further precipitation by supplies of additional water.

Gypsum may also be deposited as crusts on the borders of gypsiferous lakes, as crystals in lake muds, or as thin beds and veins by water percolating through gypsum-

Fig. 99.—Bluff exposing gypsum bed, near Hot Springs, S. Dak. (*After Darton, U. S. Geol. Sur., Bull. 223.*)

bearing beds. Dirt rich in the sulphate is known as "gypsite." In arid regions gypsite may be blown by the wind, and winnowed and thus may be separated from impurities, and may as a result form dunes composed of nearly pure gypsum sand. Such deposits are known on some of the Arizona deserts where they have been worked on a small scale.

Another, and possibly an important, source of gypsum is limestone into which sulphuric acid has penetrated.

Pyrite and other sulphides when oxidized yield H_2SO_4 which acting on $CaCO_3$ produces $CaSO_4 + H_2CO_3$. In the presence of moisture gypsum results. Perhaps some of the bedded gypsums are formed in this way.[2]

When occurring in bedded deposits gypsum is massive, crystalline or earthy, and white, gray or red. The transparent variety occurring as crystals in mudstones or in veins is known as *selenite*, and the white fine-grained massive variety as *alabaster*.

COMPOSITION

Impurities in rock gypsum include clay, calcite, ferric oxide, sand, and magnesium compounds.

The analyses of a few commercial varieties follow:

TABLE LII.—ANALYSES OF COMMERCIAL FORMS OF GYPSUM

	$CaSO_4$	H_2O	SiO_2	Al_2O_3	$CaCO_3$	$MgCO_3$
Alabaster, Mich.....	78.51	20.96	.05	.08	....	.11
Rock gypsum, Dillon, Kas.....	78.40	19.96	.35	.12	.56	.57
Gypsite, Saline, Kas.	34.38	8.50	34.35	4.11	8.14	10.52
Gypsite, Dillon, Kas.	56.58	15.16	17.10	2.04	7.71	1.24

USES

More than 95% of the gypsum mined is used in construction. Calcined to plaster-of-Paris, and mixed with something to retard its setting, it is used extensively as an inside wall plaster and in arid countries some is used as an outside finish. Gypsum plaster is used extensively in building, either pre-cast or poured into place as gypsum wall, or as plaster board, gypsum block or tile, making a good fire-resistant structure.

A special type of gypsum plaster is that commonly

[2] Stone, R. W., "Gypsum: Our Mineral Supplies," U. S. Geol. Sur., *Bull.* 666, p. 39, 1919.

known in this country as Keenes cement. It is valued because it is much harder than ordinary gypsum plaster, takes a high polish, and as commonly made is much slower setting. In general the process of manufacture is to reburn calcined gypsum which has been mixed with chemicals that will unite with the lime sulphate to form a double salt. The materials so used include potassium sulphate, sodium sulphate, potassium alum, mixtures of sodium and aluminum sulphate, and borax.

Another large use of gypsum is as a retarder in Portland cement, which without a retarder begins to set in a few minutes after mixing.

Other smaller uses of gypsum, either crude or calcined, are as land plaster or fertilizer, crayons, terra alba for fillers, plate-glass beds, pottery and terra-cotta molds, statuary and other art work, foundry molds, surgical casts, dental plaster, gypsum paint, as a substitute for horn and hard rubber in making buttons, checkers and poker chips, and even in road building in climates that are sufficiently arid. It is also used in cleaning wool and as a filler in rubber goods,[3] and in late years both gypsum and anhydrite have been extensively employed as a source of sulphuric acid, by a process that yields as a by-product a clinker, which when ground together with blast-furnace slag is sold as blast-furnace cement. Much of the sulphuric acid made from gypsum and anhydrite is used to convert ammonia obtained from the air into ammonium sulphate.

AGE

As gypsum is usually associated with rock salt it is found in rocks of the same age. It occurs with Carbonif-

[3] Stone, R. W., "Gypsum Products, Their Preparation and Uses," U. S. Bureau of Mines, *Tech. Paper* 155, 1917, and

Porter, J. M., "The Technology of the Manufacture of Gypsum Products," U. S. Bur. of Stand., *Circ.* 281, 1925.

erous beds in Virginia, Michigan, and Montana, with Silurian beds in New York and Ohio, in the Permian in Iowa, Kansas, Colorado, New Mexico and Texas, in the Triassic in the Rocky Mountain States, in the Tertiary in Arkansas and California, and in the Pleistocene in Oklahoma and Kansas.[4]

OCCURRENCES

In the United States gypsum occurs in commercial quantities in about twenty States, but more than four-fifths of the production comes from New York, Iowa, Michigan, Texas and Ohio.

In New York the commercially important beds are from 4 to 10 feet thick and are well above the salt beds.[5]

In Michigan at Grand Rapids the beds are 6 to 12 feet thick interstratified with shale and limestone. At Alabaster on Saginaw Bay a 23-foot bed of very white gypsum lies immediately beneath the drift.[6]

In Iowa, near Fort Dodge, beds from 3 to 30 feet thick are in some places overlain by red shale and in others by drift. The commercial deposits cover an area of 25 square miles. In some places lying upon the red shale are deposits of gypsite which were formed by springs issuing through the rock and bringing with their water material which they had dissolved from the beds below. This furnishes most of the gypsite that enters the trade.[7]

Gypsite has also been reported as occurring in large quantity in Panasoffkee Swamp, Florida. The deposits are a soft, incoherent mass of fine gypsum particles form-

[4] Stone, R. W. and others, "Gypsum Deposits of the United States," U. S. Geol. Sur., *Bull.* 697, 1920.

[5] Newland, D. G., "Gypsum Deposits of New York," New York State Museum, *Bull.* 143, 1910.

[6] Grimsley, G. P., "The Gypsum of Michigan and the Plaster Industry," Mich. Geol. Sur., Vol. 9, Pt. 2, 1904.

[7] Wilder, F. A., "Gypsum." Iowa Geol. Sur., Vol. 12, *An. Rept.*, 1901, pp. 99–127, 138–167, 1902.

ing little hummocks in the swamp from 8 to 10 feet high. The total quantity now known to exist in the swamp is not more than 1,000,000 tons. Its interest lies in the fact that the country rocks are Oligocene white limestones containing marl beds and layers of chert. The gypsite is supposed to have been formed by springs.

The deposits in other portions of the country are similar to those in New York, Iowa and Kansas, except that in

FIG. 100.—Gypsum mine, S. Ingonish, Nova Scotia. (*Courtesy of Mines Branch, Dept. of Mines, Ottawa, Can.*)

Virginia both gypsum and the salt associated with it seem to be limited to a narrow zone bordering a fault.

In Nova Scotia (Fig. 100) and New Brunswick gypsum occurs in great lens-shaped masses in Lower Carboniferous shales and limestones. In France it is in the Oligocene beds of the Paris Basin and in Great Britain is in the Triassic beds of Cumberland and neighboring counties. The French deposits contain 10 to 20% of $CaCO_3$ and some soluble silica which are said to increase the hardness of the set plaster.

PRODUCTION

UNITED STATES.—The quantity of crude gypsum mined in the United States in 1927 was 5,346,888 short tons of which 965,371 were sold in the crude condition for $2,388,663 and 3,912,211 tons were sold calcined at a value of $39,785,791. The balance was unsold at the end of the year.

TABLE LIII.—PRODUCTION OF GYPSUM IN THE UNITED STATES DURING 1927

(In short tons)

New York	1,675,501
Iowa	792,159
Michigan	668,617
Texas	508,382
Ohio	474,320
Nevada	327,365
Oklahoma	271,484
Other States	629,060

Of the crude gypsum 29,452 tons were used for land plaster, 29,452 tons were used in cement mills, and 3,912,211 tons were calcined.

Of the calcined gypsum 2,872,222 tons were used in plasters, 41,431 tons in Keenes cement, 18,372 tons in plate-glass works and 917,046 tons were made into blocks, boards and tile.

The imports of crude and calcined gypsum, Keenes cement and manufactures of gypsum weighed about 838,000 tons and were valued at $1,387,826, mostly from Nova Scotia. The exports were about 18,429 tons valued at $471,106.

OTHER COUNTRIES.—The largest producers of gypsum outside of the United States are: France, with a production of about 2,000,000 metric tons in normal times; Germany, with a production of about 1,500,000 tons; Canada, with a production of 880,000 tons and Great Britain, with 400,000

tons. In Canada, two-thirds of the production is from Nova Scotia,[8] but a notable quantity is produced also at various places in Ontario.[9] India produces about 40,000 tons and Bavaria and Algeria 50,000 tons each.

[8] Cole, L. H., "Gypsum in Canada," Can. Dept. of Mines, Mines Br., *Pub.* 256, 1913.

[9] Gordon, W. A., "Gypsum Industry of Caledonia, Ontario," *Eng. and Min. Jour.*, Feb. 26, 1927. See also Lanning, J., "Gypsum Deposits of Moose River," *Can. Min. Jour.*, Dec. 10, 1926.

CHAPTER X

GEMS

The minerals employed as gems are nearly all direct separations from magmas or from those portions of magmas that form pegmatites. Some of them are used only as gems. Others are used also as abrasives and some are sources or compounds employed in manufacturing specialties.

Olivine, tourmaline, beryl, opal, topaz and turquoise are used exclusively as gems or ornamental stones. Diamond, spinel, corundum, garnet, quartz and feldspar are employed also as abrasives. (See pp. 337–348.) Feldspar, quartz and certain aluminous compounds are used in the ceramic industry (pp. 360–384). Spodumene and amblygonite are sources of lithium salts (pp. 391–394), and zircon is the principal source of zirconium salts.

Only those substances that owe their main value to their use as gems are discussed in this chapter.

DIAMOND

VARIETIES AND USES

Diamond is crystallized carbon. Because of its great hardness it is used as a cutting tool, as an abrasive and in wiredrawing dies. Its brilliancy, due to its strong dispersion, makes it one of the most beautiful of gem stones.

The diamonds used in industries for boring and cutting are known as carbons, ballas and borts. They are of no value for gem purposes because of their dark color, but are much used in making diamond drills, for cutting other

diamonds and for trueing emery wheels. Carbons are black opaque groups of diamonds with no distinct cleavage. They are more or less porous, and their quality decreases as their porosity increases and their specific gravity decreases. Diamond crystals have a specific gravity of about 3.5, high-grade carbons of about 3.2 and inferior carbons of from 2.9 to 2.75. Borts are white, gray or black translucent or opaque, imperfect crystals. Ballas is a carbon in which the aggregate consists of crystals arranged about a central nucleus. Only 25,000 carats of carbons and ballas are produced annually and their price is rapidly rising.

Crushing bort is a mixture of small, broken and inferior diamonds that are crushed to make diamond dust for use in polishing and grinding hard substances. The production of this low grade material is about 1,000,000 carats per annum with a value of about $4.00 per carat,[1] but it could be greatly increased if there were an increased demand.

MANNER OF OCCURRENCE AND ORIGIN

Diamonds occur as loose pebbles in glacial and alluvial sands and gravels and as crystals embedded in a certain variety of the rock peridotite, known as kimberlite.

There is a small production of diamonds from the drift in the United States, varying in value from a few hundred dollars to $6,500 annually. In the past most of these have been found in the glacial drift of Indiana and Wisconsin, in the soil of Virginia and other Southern Appalachian States, and in the gold-bearing gravels of California. Most of the finds are small stones, valuable only because of their rarity, but one of them (the Dewey Diamond), discovered in a spring near Richmond, Va.,

[1] The metric carat, which is now universally used, to express the weights of diamonds, is equal to 200 milligrams.

was valued at $500.00. The source of these diamonds is unknown, but they are supposed to be a part of the detritus of diamond-bearing rocks, existing at points far distant from those at which the gems are now found. Those in the drift perhaps originated in Canada.

During the past few years diamonds have also been obtained from a weathered peridotite in Arkansas.

In Brazil diamonds are found in a conglomeratic and false-bedded sandstone, the Lavras series, along the river courses in the State of Bahia.[2] Here the product is mainly carbonado—a black or dark-brown diamond without distinct cleavage. This is used chiefly in diamond drills. As a rule the size of the stones varies directly with the coarseness of the conglomerate, which is unconformably beneath a series of red sandstone, shales and limestones of Permian age. The best carbonado is becoming so scarce that its price is almost as high as that of some gem diamonds.[3]

In Southern Africa the diamonds that occur in the mines are in necks of kimberlite that cut through a series of sandstones, lavas and shales. The crystals are embedded in the kimberlite, which contains also abundant inclusions of carbonaceous shales. The diamonds appear to have crystallized from the magma that gave rise to the rock, but whether the carbon was in the magma originally or was incorporated into it by solution of shale fragments is a moot question.[4]

[2] Derby, O. A., "Speculations Regarding the Genesis of the Diamond," *Jour. of Geol.*, Vol. 19, pp. 627–631, and Vol. 20, pp. 451–456, 1912.

[3] Garrison, J. L., *Eng. and Min. Jour.-Press*, Vol. 118, p. 491, 1924.

Derby, O. A., "The Geology of the Diamond and Carbonado Washings of Bahia, Brazil," *Econ. Geol.*, Vol. 1, pp. 134–142, 1905.

Crandall, R., "Notes on the Geology of the Diamond Region of Bahia, Brazil," *Econ. Geol.*, Vol. 14, pp. 220–244, 1919.

Thompson, L. S., "Upland Diamond Deposits, Diamantina District, Minas Geraes, Brazil," *Econ. Geol.*, Vol. 23, pp. 705–723, 1928.

[4] Clarke, F. W., "The Data of Geochemistry," U. S. Geol. Sur., *Bull.* 770, pp. 328–330, 1924.

The kimberlite weathers rapidly to a clay. On the surface this is yellow but beneath the surface, where it has not been oxidized, the material is blue. The "blue ground" contains from 0.2 to 0.6 of a carat of diamonds per cubic yard. The rock is spread on the ground to weather further and when sufficiently disintegrated is mixed with water and the resulting mud is passed over plates smeared with grease to which the diamonds adhere.

The largest gem diamond in the world—the Cullinan—was picked up at the Premier Mine.[5] It weighed 3,025 carats before cutting.

One of the most interesting occurrences[6] of diamond is at Olivine Mt., Tulameen District, B. C. The rock is a serpentinized peridotite containing concretions of chromite that are unquestionably segregations from the magma, and associated with these diamonds are found. They are small, yellowish or brown and opaque, and are of no value, but they indicate clearly that some diamonds at any rate may crystallize directly from magmas. The same fact is indicated by the discovery of diamonds in meteorites.

IMPORTS

During the late war the United States was the only country in which people were buying diamonds and consequently the importations were large. Immediately after the war with the advent of dull times importations fell off. They are now beginning to increase again.

In 1910, 1914, 1919 and 1927 the imports of diamonds of all kinds were as follows:

[5] Penrose, R. A. F., Jr., "The Premier Diamond Mine, Transvaal, South Africa," *Econ. Geol.*, Vol. 2, pp. 275–284, 1907.

[6] Camsell, C., "A New Diamond Locality in the Tulameen District, B. C.," *Econ. Geol.*, Vol. 6, pp. 604–611, 1911.

TABLE LIV.—IMPORTATIONS OF DIAMONDS INTO THE UNITED STATES, 1910–1927

	Glaziers'	*Dust, Bort, Etc.*	*Uncut*	*Cut*
1910	$ 213,701	$ 54,701	$ 8,991,890	$25,593,641
1914	579,332	77,408	2,851,933	11,976,871
1919	984,381	1,420,442	20,306,758	64,085,610
1927	2,149,912	320,408	11,470,026	40,736,351

PRODUCTIVE FIELDS

UNITED STATES.—In the United States the only diamond fields of note are in Arkansas,[7] where the conditions are the same as in Africa, i.e., the diamonds occur in a peridotite that cuts shales (Figs 101 and 102). In 1918 several hundred carats were reported from Murfreesboro, including a clear flat stone weighing 11 carats, a canary-colored octohedron weighing 17.85 carats and several other stones weighing several carats each. Prior to the end of 1914 over 2,000 stones had been found weighing about 550 carats valued at $12,000.

UNION OF SOUTH AFRICA.—About 65% of the diamonds of the world at present come from the Union of South Africa. About half of these are produced from mines near Kimberley in Northern Cape Colony, near Jagersfontein in the Orange Colony and near Pretoria in the Transvaal, the most famous mines being the De Beers Consolidated and the Premier, and the other half from alluvial diggings in Lichtenburg and at other places in Bechuanaland and in Namaqualand, in the neighborhood of Alexander Bay, between Port Nolloth and the mouth of the Orange River (Fig. 103).

[7] Miser, H. D., "New Areas of Diamond-bearing Peridotite in Arkansas," U. S. Geol. Sur., *Bull.* 540, pp. 534–546, 1912.

Miser, H. D., and Ross, C. D., "Diamond-bearing Peridotite in Pike County, Arkansas," U. S. Geol. Sur., *Bull.* 735, pp. 279–322, and *Econ. Geol.*, Vol. 17, pp. 662–674, 1922.

The yield of the three mines of the De Beers Company that were operating in 1927 was about 1,133,873 carats, or about one-fourth carat per load of blue ground washed,

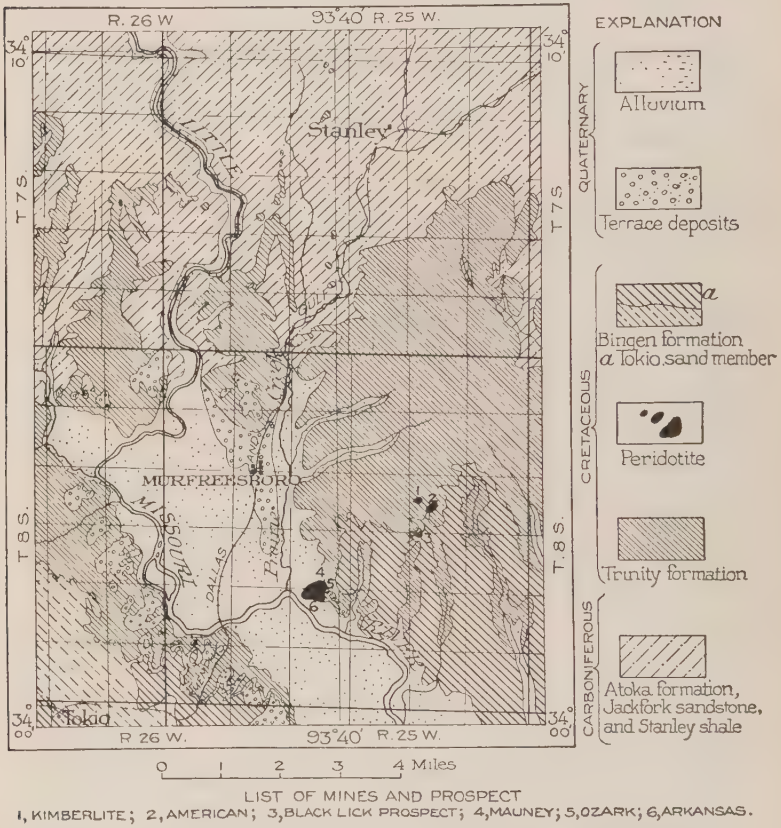


FIG. 101.—Geological map of Pike County, Ark., showing location of peridotite areas and diamond mines. (*After Miser and Ross, Economic Geology, Vol. 17.*)

and that of the Premier Company, which was operating on part time only, was 955,302 carats, with an average value of $5.00 per carat, and an average yield of one-fifth carat per load. The total production of all the mines in 1927 was 2,389,631 carats valued at $30,000,000. Since 1867,

when mining began, the total production has amounted to about 40 tons of stones valued at about $1,280,000,000 and the present known reserves in the mines are said to be sufficient to keep up the supply for more than 100 years.

The alluvial diggings in South Africa, in Bechuanaland and Namaqualand, were so productive in 1927 that their yield was as great as that of the mines, and the stones were

FIG. 102.—Altered volcanic breccia containing diamonds, in cut at Ozark Mine, Murfreesboro, Ark. (*After Miser and Ross, Economic Geology, Vol. 17.*)

of a little better grade. The total production of the Union was 4,708,038 carats valued at $60,000,000.

GERMAN SOUTHWEST AFRICA.—Another large producer of diamonds is German Southwest Africa, now the Southwest Protectorate, from which about $7,000,000 worth of the gems are obtained annually. Here the diamonds are in gravel and wind-blown sand resting on a crystalline rock that is not peridotite. It is possible that the occurrence here is somewhat like that in Brazil and that the stones have been transported from elsewhere.

Gold Coast.—A new discovery in the Gold Coast Colony may become of importance. The stones in this field are in gravels, and are of small size, ranging from a pin-head to a split pea. Many of them are beautifully crystallized and most of them are tinted. Their value is thought to range between $2.50 and $75.00 a carat. The stones are known to be distributed through the gravel in

Fig. 103.—Sketch map showing positions of phosphate deposits and diamond-bearing areas in Africa.

enormous numbers, the reserve of a single company being estimated at 9,000,000 carats.

The production in 1927 was 426,400 carats.

Tanganyika Territory.—Another discovery, in Tanganyika Territory at the southern end of Lake Victoria, is now being developed. The diamonds occur in a peridotite as at Kimberley, and are of excellent grade, those produced in 1927 bringing $30.00 per carat. Moreover,

the yield of the rock is high. In 1927 the yield per load was 8.62 carats, and the total production was 17,168 carats that were sold for about $450,000.

Congo and Angola.—The largest alluvial field in the world is in northeast Angola and the neighboring part of the Belgian Congo. It covers about 150,000 square miles and is worked by 40 mines and 24,000 men. The production in 1927 was about 1,176,000 carats.

British Guiana.—Although by far the greater portion of the diamonds of the world come from the southern half of Africa a large production of good stones is now being made in the interior of British Guiana from alluvial deposits. The extent of the productive area is over 6,000 square miles, extending from the Potaro to the Cuyuni rivers, a distance of 150 miles, and eastward 40 miles from the foot of the Pakaraima Mountains. The quality of the diamonds obtained in 1926 warranted a price of $22.00 per carat.

The diamonds are found in shallow deposits with quartz pebbles, tourmaline, ilmenite, ferromagnesian minerals and gold. The pay gravel is from 6 inches to 1 foot thick and the average weight of the stones is one-sixth of a carat, though a few have been found weighing from 8½ to 24¼ carats.

Other localities.—The occurrence of diamonds in Brazil has already been referred to.

Gem diamonds have been produced for ages from the Madras Presidency in India and from the Island of Borneo, but these sources are not now productive except in a small way, and the manner of association of the stones is not known. Some of them seem to have come from pegmatites.

PRODUCTION

About 97% of all gem diamonds are produced in Africa and nearly all the carbonado comes from Brazil.

TABLE LV.—WORLD PRODUCTION OF DIAMONDS IN 1927
(The figures are approximations)

	Carats	*Value*
Union of South Africa:		
Mines	2 389,631	$30,000,000
Alluvial	2,318,407	30,000,000
Protectorate of Southwest Africa	500,000	6,500,000
Belgian Congo	975,000	9,500,000
Angola	201,000	2,000,000
Gold Coast and West Africa (a)	340,020	2,000,000
Tanganyika	17,168	450,000
British Guiana	173,797	3,500,000
Brazil (a)	34,018	1,670,000
TOTAL	6,950,000	$85,620,000

(a) Exports.

In order to prevent the overstocking of the market all diamonds produced in South Africa are sold by a syndicate. According to an agreement made since the war, the syndicate decides as to the quantity of stones it will put on the market during a certain period and purchases them from the producers according to the following quotas:

	Per cent
De Beers Company	51
Southwest Protectorate Producers	21
Premier Company	18
Jagersfontein Company	10

By this agreement the syndicate monopolizes a large part of the world trade in diamonds and guards against a fall in prices. As the Premier mine alone has 37,000,000 loads of blue earth available above its present lowest working level, it is evident that without such control of the market the production of diamonds would inevitably soon increase, with a probable decrease in their selling price.

Since, however, the syndicate controls only the output of the alluvial diggings of Angola, the Belgian Congo and the Southwestern Protectorate, in addition to that of the mines in the Union of South Africa, it is evident that with the increase in the output of alluvial diggings elsewhere, the monopoly of the syndicate may before long be broken. This seems all the more probable in view of the fact that mine stones are on the whole inferior to alluvial stones, and that in 1927 the yield of the alluvial diggings was twice as great as that of the mines. Indeed, the rapid increase in the production of alluvial stones—from about 2,750,000 carats in 1926 to 4,350,000 carats in 1927—caused the South African parliament to pass a bill giving the Minister of Mines general control of the mining and disposal of precious stones produced in the country, resulting in the prohibition of all diamond prospecting throughout the Union for the period of one year.

OLIVINE

Peridot is the jewelers' name for olivine ($(Mg.Fe)_2SiO_4$). It is yellowish-green and transparent, but is too soft to be of great value as a gem. From $100 to $1,000 worth is produced annually from the western part of this country. It is found scattered as loose grains in the soil at Fort Defiance and Rice in Arizona, where it has resulted from the disintegration of a basic volcanic rock of which it is a component. In some years as much as $8,000 is collected and sold.

In Hawaii an area of decomposed lava is characterized by the presence of numerous crystals of peridot in the overlying soil. This is scraped and the scrapings are sifted, or the crystals are picked from the sandy soil after rains. Many of these stones cut into gems weighing 1½ carats. It is said that in 1918 four men working five days saved 30,000 fragments of the mineral.

TOURMALINE

Tourmaline is the name of a series of compounds of the general formula $R_9Al_3(B.OH.F)_2Si_4O_{19}$. When R = K, Na, Li, the mineral is colorless, red or green and transparent, and is used as a gem. When R = Fe, in part, black varieties result. These are used in optical instruments to produce polarized light. When R = Mg, brown varieties result. Some of these are translucent and are used to a slight extent as gem material. When R = Mn the color depends upon the proportions of Fe to Mn present. When the ratio is 1:1 the mineral is colorless, blue, pale pink, or pale green. An excess of Mn deepens the red tint and of Fe the green or blue tints.

The varieties recognized by distinct names are ordinary, black or brown; indicolite, blue; rubellite, red or pink and transparent; Brazilian sapphire, transparent blue; Brazilian emerald or Brazilian chrysolite, green and transparent; peridot of Ceylon, honey-yellow and transparent, and achroite, colorless. All the transparent varieties are used as gems, but their colors are so brilliant, that the gem is not a favorite one except for sets in rings.

The mineral occurs in pegmatite dikes, especially in hollows surrounded by projecting quartz crystals.

The annual production of gem tourmaline in the United States varies between $7,500 and $50,000, its value depending more upon the size and brilliancy of the material than its quantity.

Gem material comes from the soda lithia pegmatites in western and central Maine,[8] (Fig. 104), at Haddam, Conn., and in San Diego and Riverside counties, California.[9] In

[8] Wade, B., "The Gem-bearing Pegmatites of Western Maine," *Eng. and Min. Jour.*, June 5, 1909.

Bastin, E. S., "Geology of the Pegmatites and Associated Rocks of Maine, Including Feldspar, Quartz, Mica and Gem Deposits," U. S. Geol. Sur., *Bull.* 445, 1911.

[9] Kunz, G. F., "Gems, Jewelers' Materials and Ornamental Stones of California," Calif. Stat. Min. Bur., *Bull.* 37, 1905.

all these localities it occurs in miarolitic cavities in the pegmatites where it is associated with the pink lithium mica, lepidotite.

The finest red and green gems come from Minas Geraes in Brazil and Madagascar; deep rubellite from Siberia; yellow and brown tourmaline from Ceylon and Carinthia,

FIG. 104.—Large pocket in pegmatite, Mt. Mica, Me. (*After Bastin, U. S. Geol. Sur., Bull. 445.*)

Austria, and pink tourmaline from Elba. In most of these countries the gem occurs in cavities in pegmatites, but in Madagascar and Ceylon large numbers are found in the stream gravels derived from pegmatites.

The value of the tourmaline produced in the United States during 1922 is estimated at $17,700. Ball's estimate [10] of the average total value of tourmaline produced in the world is $90,000.

[10] Ball, S. H., "The Geologic and Geographic Occurrence of Precious Stones," *Econ. Geol.*, Vol. 17, pp. 575–601, 1922.

BERYL

Beryl ($Be_2Al(SiO_3)_6$) is another gemstone found mainly in pegmatite dikes, where it occurs under the same conditions as tourmaline, to a very small extent in contact metamorphic schists and in the gravels of streams draining rocks cut by pegmatites. It occurs in large massive translucent masses and in yellow, green or colorless crystals. The transparent varieties are used as gems. They are designated by the names:

Emerald—deep-green	Rose beryl
Aquamarine—blue-green	Blue beryl
Golden beryl—topaz colored	White beryl

All are valuable, the emerald being especially so, some Colombian stones having brought $150,000 each. About $2,000 worth are annually produced in the United States, mainly from western North Carolina.[11] Aquamarine, rose beryl and golden beryl come from North Carolina, Georgia, Maine and Connecticut.[12]

The finest emeralds come from Colombia [13] where they occur in pegmatite-like veins in a clay slate, and from Bajenovo, in the Ural Mountains, Russia. Others come from Zobara near the Red Sea, from the Tirol, in Italy, from Minas Geraes, Brazil, and from West Australia, Hindustan and Ceylon. The finest aquamarines are from points in Siberia. In 1927 a promising occurrence of gem beryl was discovered near Gravelotte, in northern Transvaal. Very little work has been done on it, but the few stones that were obtained have been valued at from $20.00 to $100.00 per carat. In Brazil [14] the emeralds

[11] Kunz, G. J., "History of the Gems Found in North Carolina," N. C. Geol. and Econ. Sur., *Bull.* 12, pp. 37–45, 1907.

[12] Kunz, G. F., *Gems and Precious Stones of North America*, New York, 1890.

[13] Pogue, J. E., "The Emerald Deposits of Muzio, Colombia, South America," Am. Inst. Min. Eng., *Trans.*, 1916, pp. 799–822.

[14] Just, Evan, "Emeralds at Bom Jesus dos Meiras, Bahia, Brazil," *Econ. Geol.*, Vol. 21, pp. 808–810, 1926.

occur associated with crystallized quartz and calcite in geodes in a metamorphosed lower Paleozoic marble.

The total value of the annual beryl production of the world, according to Ball,[15] is $650,000 of which $550,000 is the value of emerald.

TOPAZ

Topaz ($Al(Al(F.OH)_2)SiO_4$), though abundant in acid igneous rocks, is not common in gem quality in the United States. The quantity produced annually is valued at about $500. It is found mainly in pegmatites, but also in veins with cassiterite (SnO_2), in granites and other acid igneous rocks and near contacts of limestones with pegmatites. It is distinctly a pneumatolytic mineral, or one produced by the gases that are extruded from cooling magmas. The gem material is obtained from pegmatites or from stream gravels.

In the United States topaz occurs on the walls of cavities in igneous rocks at Nathrop, Colorado, and in the Thomas Mts. in Utah,[16] and also in pegmatites at Stoneham, Maine and at Trumbull, Connecticut. The best gem topaz comes from Schneckenstein and Ehrenfriedensdorf, in Saxony, from Jekaterinburg and the Ilmengebirge, Russia, from pegmatite at Sakangei, Burma,[17] from veins in Minas Geraes, Brazil, and from sands containing cassiterite in Mexico. One crystal found in Brazil weighed at least 300 lbs., according to Kunz.[18]

Ball's estimate of the annual topaz production of the world is $20,000.

[15] Ball, S. H., l. c.

[16] Patton, H. B., "Topaz-bearing Rhyolite of the Thomas Range, Utah," Geol. Soc. Amer., *Bull.* 19, pp. 177–192, 1908.

[17] Adams and Graham, Roy. Soc. Can., *Trans.*, Sec. 4, p. 124, 1926.

[18] Kunz, G. F., "Gems, Jeweler's Materials and Ornamental Stones of California," Calif. State Min. Bur., *Bull.* 37, 1905.

ZIRCON

Zircon ($ZrSiO_4$) is employed to a small extent as a gem. Its principal use is as a source of zirconia (p. 384). The transparent red or orange variety is hyacinth, the yellow is jacinth and the white is jargon. Matara diamonds are pale-brown zircons that have been decolorized by heat, and blue zircons are brown stones that have been heated in fumes of a mixture of cobalt nitrate and potassium ferrocyanide.

Gem zircon occurs only in pegmatite dikes and in stream gravels. The annual production of ordinary zircon throughout the world is valued at about $7,100 nearly all of which is found in stream gravels. The blue zircon is all from near Bangkok in Siam. It has been named "Starlite," and under this name has been sold to the extent of $100,000.

QUARTZ

Quartz (SiO_2) is used for a great variety of purposes. Because of its hardness it is employed as an abrasive (p. 346). Because of its characteristic chemical properties it is used in making pottery and in metallurgical and chemical processes (pp. 356–359), and because of its physical properties it is melted to make silica glass. Transparent crystallized quartz is used as a gem.

Clear colorless varieties, known as rock crystal, are used in optical instruments, under the name Brazilian pebble, and as decorative stones under the names rhinestone and Saratoga diamond. Colored transparent varieties include the gems rose quartz, smoky quartz or Cairngorm stone and amethyst. Masses of interbanded quartz and chalcedony are agates. They are used as ornamental stones and as bearings for light machinery. Citrine, or false topaz, sagenite, rock crystal enclosing rutile needles, and

aventurine, rock crystals spangled with scales of a micaceous mineral, are other forms of gem quartz. Carnelian, chrysoprase, prase, plasma and bloodstone or heliotrope are forms of chalcedony. Onyx and sardonyx are evenly banded agates.

Gem quartz occurs mainly in pegmatites and veins, but some amethysts and most agates are from geodes in limestone. In some cases deposition was by cool meteoric water and in others by hot magmatic water. The meteoric water obtained silica from silicates decomposed by weathering processes.

Gem quartz, including colorless varieties, was produced in the United States to the value of $35,000 in 1915, $28,000 in 1917 and $17,632 in 1919. Good amethysts and agates occur in the rocks on the north shore of Lake Superior. Rose quartz occurs in large quantity at Hebron and other places in northwest Maine and near Exeter, Tulare County, California, and the best smoky quartz at Paris, Maine, and in Alexander County, North Carolina.

The best agates and amethysts are imported. Many are obtained in Uruguay, which probably is now the main source of both materials. The annual production of amethyst is about 15,000 lbs., ranging in value from 11 cents to $41.00 per kilo (2.2 lbs.). The quantity of agate obtained is unknown. It is, however, large. Both materials occur in geodes in limestone. Recently a discovery of amethyst near Pretoria, South Africa, has been reported, and about 6,000 lbs. of good material is said to have been shipped.

The finest rock crystals come from Dauphinè, France; Carrara and the Piedmont district, Italy, and from the State of Bahia in Brazil. Smoky quartz of gem quality is obtained at many points in Scotland, and the finest amethysts in Uruguay, Ceylon, Brazil and Nova Scotia. The best agates come from Arabia, India and Brazil.

OPAL

Opal is a colloidal hydrate of silicon. It is known to be formed by the weathering of silicates. It precipitates from hot and cold water. It is found in veins in volcanic rocks and embedded as nodules in limestones, where it apparently has been formed by the solution of siliceous spicules, or by the solution of the finely divided silica that is nearly always present in limestones and dolomites.

The purest opal is transparent and colorless, or light-colored. It is used as a gem. The play of colors observable in the best specimens is due to the interference of light rays reflected from the sides of thin layers of opal material with different densities from that of the main mass.

Precious opal of gem quality is found near Kashan, Hungary; at Queretaro and Zimapan, in Mexico; in Queensland, New South Wales, South Australia, and at various localities in Honduras, Washington, Nevada and Oregon. The deposit at Winnemuca, Nevada, is one of the largest in the world, but the stones fall to pieces if dried rapidly, and consequently have to be buried for several years in clay, so that they may lose their excess water slowly and become "tempered." In all cases opal occurs in veins believed to result from the action of hot magmatic waters upon the silicates of rocks through which they pass. Pieces of rock traversed by tiny veins are known as opal matrix.

Opalized wood from the petrified forests of Chalcedony Park, Arizona and Nevada, are sawed, polished and used for ornamental purposes. Often the texture of the wood remains and veins of precious opal traverse the mass. Formerly the material was taken without reference to ownership, but now that destruction of the trees is for-

bidden by Congress the trade in opalized wood has practically ceased, though small quantities have recently been produced at Virgin Valley, in Humboldt County, Nevada.

The principal varieties of precious opal are:
Hyalite, clear and colorless,
Fire opal, with brilliant red reflections,
Girasol, a bluish-white translucent variety with red reflections, and
Cacholong, an opaque, bluish-white, porcelain-like variety.
Flint and chert are mixtures of opal, chalcedony and quartz.

The value of opal produced in the United States during 1917 was only $805, and in 1918 $6,304 but in 1913 as much as $15,000 was sent into trade. The total production of the world is worth about $60,000 annually, of which $45,000 was credited to South Australia in 1927.

TURQUOISE

Turquoise (an acid copper aluminous silicate) is the only important gem material formed by circulating meteoric water. It is a product of surface action and consequently is confined to the upper part of the Earth's crust.

The mineral occurs in small veins cutting decomposed acid, volcanic rocks and other rocks in contact with them, in grains disseminated through both intruding and intruded rocks, in globular masses and crusts coating cracks in them and in little stalactites attached to the walls of cavities in them.

Turquoise of gem quality is blue, but most of the mineral, especially that exposed on the surface, is light-green or very pale, blue or white. The mineral is polished and used as a gem. Pieces of rock containing veinlets of turquoise are sold under the name of turquoise matrix.

Turquoise occurs abundantly in the Cerillo Mountains and in the Burro Mountains in New Mexico, near Millers in Nevada, in Mineral Park, Arizona, and at LaJara, Colorado. Several of these places are the sites of mines that were worked by the Mexicans in olden times, and have been reopened within recent years.

The best turquoise comes from Nishapur in Persia, from the Megara Valley, Sinai and from near Samarkand in Turkestan.

In some years the yield of turquoise in the United States has reached a value of $150,000 but in 1922 only $22,750 worth was produced. The world's yield is valued at about $290,000 annually (Ball).

OTHER GEMS AND PRECIOUS STONES

Spinel.—Spinel ($Mg(AlO_2)_2$) occurs in contact metamorphosed limestone and in stream gravels. The transparent red spinel is known under the name of ruby spinel.

Only small quantities of spinel are produced in the United States. Ball estimates that the annual production of spinel in the world is valued at $20,000.

Spinel is also a constituent of some forms of emery. (See pp. 341–343.)

Jade.—Jade was formerly a valued medium for carving into charms and religious emblems. It was especially highly regarded in China, Thibet, Mexico and South America. At present it is mined systematically only in Burma. The material is a mixture of diopside ($(Mg.Ca)SiO_3$) and jadeite ($NaAl(SiO_3)_2$), both of which are pyroxenes. Its color is white, green or gray-green. The valuable varieties are translucent and have a very fine-grained, uniform crystalline texture and a splintery fracture. Nephrite, also used as jade, is a fibrous tremolite or actinolite.

The sources of the great amount of jade in the orna-

ments found in China and Mexico are not known. In Burma the mineral jadeite is found with albite and nepheline in a dike at Tawman. The production in Burma during 1924 was 2,630.4 cwt.

LAZULITE.—Lazulite ($(Mg.Fe)(AlOH)_2(PO_4)_2$) is used to a small extent in the manufacture of small ornaments. It occurs as bright-blue pyramidal crystals in quartz veins and in serpentine.

In the United States it has been reported at Crowder's Mountain in North Carolina and at Graves Mountain in Georgia. It occurs also at Krieglach in Styria and at Horrsjöberg in Sweden. Comparatively large amounts are said to exist at Tijuco, in Minas Geraes, Brazil, and near Santa Rita in the same State.

BRUCITE ($Mg(OH)_2$) occurs in limestone and serpentine, associated with magnesite and hydromagnesite. A light green massive variety at Chewelah, Washington, is carved and turned into ornaments. While easy to carve, it is too soft to stand hard usage.

VESUVIANITE, a basic calcium-aluminous fluo-silicate, occurs in contact metamorphosed gneiss, schists, and limestones and in serpentine, associated with garnet, tourmaline and other contact minerals. A green, massive variety, at Happy Camp, Siskiyou County, California, is used as a gem stone under the name californite. Clear, transparent varieties from other places are also used as gems to a small extent.

LAPIS LAZULI is a mixture of various substances in which the blue compound ($Na_2(NaS_3.Al)Al_2(SiO_4)_3$) is prominent. Lasurite is a contact mineral in limestone. The mixture which it colors is used as an ornamental stone in the carving of vases, in the manufacture of mosaics, and after grinding is employed as a pigment.

Good material occurs near Lake Baikal in Siberia, in the Andes Mountains, near Ovalle in Chile, in the Alban

Mountains in Italy and at various places in Persia, Afghanistan, Eastern Russia, Central China and Tibet. It has not been found in North America. The chief sources of supply are in Afghanistan and Persia.

Malachite ($(CuOH)_2CO_3$), the green, fibrous and stalactitic copper carbonate, occurs in abundance in the upper portions of veins of copper ore where it was formed by the weathering of copper compounds. It is found in the United States as large masses in the mines at Bisbee and Morenci, Arizona, in the Tintic district, Utah, and in smaller masses elsewhere. It is particularly abundant in the copper mines in Russia and Germany.

In some places it is mixed with the bright blue azurite ($Cu(CuOH)_2(CO_3)_2$).

Masses of malachite are sawn into slabs and polished for use as table tops and wainscotting, and are turned into vases, pedestals and columns.

Only a small quantity is used in the United States, but fairly large quantities are employed in Russia for veneering clock cases and ornamental boxes.

Beryllonite ($NaBePO_4$), herderite ($CaBe(OH.F)PO_4$), and phenacite (Be_2SiO_4) are colorless minerals with high indices of refraction which give them a sparkle, so that they have been used to a small extent as gems. Beryllonite and herderite are found in pegmatites at Stoneham, Maine, and phenacite at Greenwood, Maine, at Topaz Butte and Mount Antero in Colorado, in Durango, Mexico, at the emerald mines in the Ural Mountains, and elsewhere.

Other minerals that are used in small quantity as ornamental or gem stones are hiddenite, kunzite (p. 392), hematite, rutile, epidote, apatite, aragonite, titanite and several less common ones.

CHAPTER XI

ABRASIVES

The principal natural substances used as abrasives are corundum and emery, garnet, quartz, including sand, sandstone and grit, pumice, pebbles, tripoli, infusorial earth, and to a small extent diamond and feldspar. Diamond has already been discussed because its value depends principally upon its use as a gem. (See p. 315.) Corundum, garnet, quartz and feldspar are also employed as gems, but all these minerals except feldspar are more important as abrasives. Feldspar is of value mainly as an ingredient in the manufacture of ceramic products. (See p. 368.) Quartz serves many uses. Gem quartz has already been treated (p. 330). Vein quartz and quartz sand are more important as sources of silica in the manufacture of glass and ceramic products (p. 356), and in addition sand is used for many special purposes.

For the manufacture of abrasive material bauxite and certain other aluminous minerals have recently come into wide use. Since, however, they are not used directly as abrasives their discussion is more properly given in the chapter on ceramic materials (pp. 375–384).

CORUNDUM AND EMERY

Corundum.—Corundum (Al_2O_3) occurs in alkaline acid and basic rocks, where it separated from magmas containing an excess of alumina, and in the debris produced by their decomposition. Because of its great hardness it is used as an abrasive, and because of their coloring and high index of refraction transparent varieties are employed as gems, under the names sapphire and ruby. In

most places the mineral occurs as crystals, grains and irregular masses near the borders of peridotite intrusions, though in Canada and elsewhere it is found in a series of nepheline rocks cut by syenite pegmatites. The corundum occurs as large grains or crystals in both these rocks.

The main productive occurrences of corundum in the United States are in Western North Carolina,[1] in Rabun County, Georgia,[2] and in Gallatin and Fergus counties, Montana.

In North Carolina the mineral occurs in lumps around the borders of a mass of olivine rock known as dunite (Fig. 105). The lumps are usually enclosed in layers of micas. Wherever dunite occurs in the Appalachian district, all the way from Massachusetts to Alabama, corundum accompanies it; but it is only in North Carolina and Georgia that the mineral is abundant enough to warrant working. The corundum was probably one of the earliest minerals to crystallize from the magma, and therefore is now near its borders. Formerly nearly all production in the United States was from North Carolina, but the mines are now inactive.

Corundum grains are used as abrasives for certain purposes for which artificial abrasives are not suitable—especially for making corundum wheels.

All of the corundum used in the United States is imported. In some years a small part of it comes from Canada, where it is an important component of nepheline syenites and intersecting pegmatites at Craigmont, Ontario.[3] Most of it, however, comes from Russia,

[1] Pratt, J. H., "Corundum and Its Occurrence and Distribution in the United States," U. S. Geol. Sur., *Bull.* 269, 1906.

Pratt, J. H., and Lewis, J. V., "Corundum and the Peridotites of Western North Carolina," N. C. Geol. Sur., Vol. 1, 1905.

[2] King, F. P., "A Preliminary Report on the Corundum Deposits of Georgia," Ga. Geol. Sur., *Bull.* 2, 1894.

[3] Barlow, A. E., "Corundum, Its Occurrence, Distribution, Exploitation, and Uses," Can. Geol. Sur., *Mem.* 57, 1915.

Madagascar, India and the Transvaal. The total imports into the United States during 1926 were about 5,420

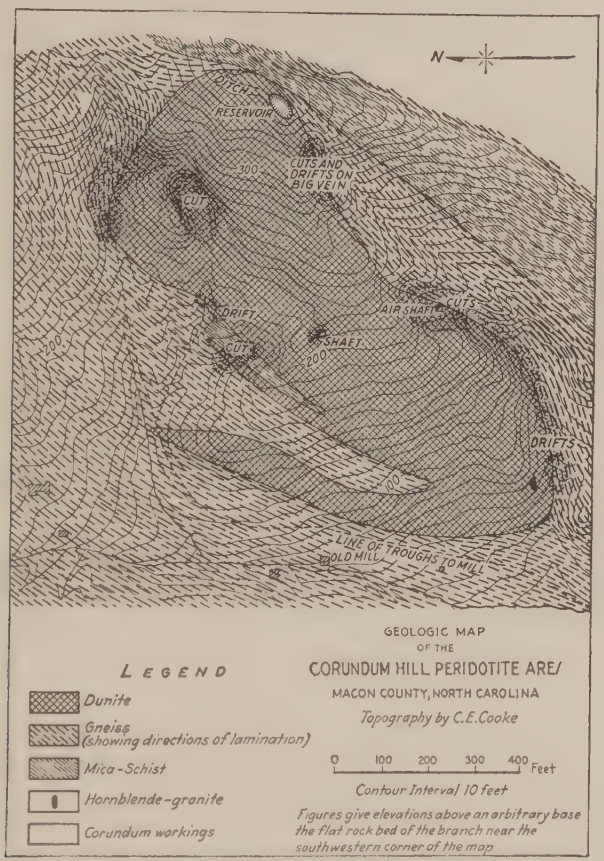


FIG. 105.—Map of Corundum Hill peridotite area in Macon Co., N. C., showing positions of the corundum diggings, mainly near the margins of the peridotite. (*After Pratt and Lewis, N. C. Geol. Sur., Vol. I, 1905.*)

short tons of crude and prepared material valued at $310,000.

The Canadian deposits are large but they are expensive to work, as the corundum-bearing rock must be crushed

and the corundum separated by mechanical means in a district where labor is scarce, and the yield is only 12 to 15% of the material handled.[4]

In India the occurrences are like those in North Carolina and Georgia.

The output of the Transvaal is from narrow vertical veins and their decomposition products. Most of the mineral is obtained from the soils which are corundum-bearing over an area measuring 2,000 square miles.

Sapphire and ruby.—Transparent gem corundum, or sapphire, is found in corundum-bearing rocks. Fine gems were formerly obtained in the streams draining the peridotite areas in North Carolina and Georgia but no recovery has been reported from this district in the past few years.

The most productive occurrences in the United States are at Yogo Gulch, Fergus County, Montana, and in the sands along the Missouri River, near Helena, Montana. At Yogo Gulch the sapphires are in well-defined crystals in a lamprophyre dike,[5] where they are supposed to be due to the solution of shales in the dike matter. The rock is mined, allowed to slack and is then washed in sluice boxes.

At Helena the sapphire-bearing sands extend for 20 miles. The sapphire comes from dikes something like those at Yogo Gulch, but they have not yet been worked. The gems are prismatic and most of them are greenish or yellow.

[4] A comprehensive, but brief, account of the occurrence of corundum-bearing rocks in Canada, and short descriptions of corundum occurrences in other countries, are given by Eardley-Wilmot, V. L., "Abrasives. Pt. II. Corundum and Diamond," Can. Dept. of Mines, Mines Br., *Pub.* 675, 1927.

[5] Pirsson, L. V., "On the Corundum-bearing Rock from Yogo Gulch, Mont.," *Am. Jour. of Sci.*, Vol. 4, pp. 421–423, 1897, and Weed, W. H., U. S. Geol. Sur., *20th An. Rept.*, Pt. III, p. 454–459, 1899.

Sterrett, R. B., "Sapphire (in) Montana," U. S. Geol. Sur., *Min. Res.*, 1907, Pt. II, pp. 816–824, 1908.

Rubies and sapphires are known in New York, Canada, and elsewhere in limestones cut by igneous dikes, but nowhere in large enough quantity to be worked commercially.

Most of the sapphires and rubies from United States localities are used as bearings in fine machinery, like watches, but some of those found in North Carolina have furnished handsome gems. The place of sapphires in machinery, however, is rapidly being taken by artificial sapphires.[6]

In 1925 the production of sapphires in Montana aggregated 266,368 carats valued at $33,375, of which 54,495 carats valued at $29,138 were sold for gems and 211,873 carats valued at $4,237 were sold for mechanical purposes.

The best sapphires come from Siam, Burma, Ceylon and Queensland. In most places they are found in gravels, but in Burma rubies occur in metamorphosed limestone, and sapphires in pegmatite. The most valuable rubies come from the Mandalay, Mytkynia and Mogok districts in Burma.[7] In Ceylon excellent sapphires are found in the rice fields at Pelmadula in a thin layer of gravel under a layer of clay from 10 to 20 feet thick. The gems are so abundant that within several years stones to the value of $300,000 have been obtained by crude methods from an area between 3 and 4 acres in extent.

During 1925 the exports of rough sapphires from Siam were valued at about $20,000 and in 1924 at about $140,000. The Queensland production during these two years had a value of about $170,000. The Burma ruby mines produced rubies to the value of about $110,000.

Emery.—Emery is an impure corundum or rather a mixture of corundum, magnetite and hematite, or of these

[6] "The Synthetic Production of Rubies, etc.," *Min. Sci.*, June 27, p. 546, 1912.

[7] Adams, F. D., "A Visit to the Gem Districts of Ceylon and Burma," Can. Inst. Min. and Metallurgy, *Trans.*, Vol. 29, 1926 and Smithson. Rept., 1926, pp. 297–318, 1927.

minerals and spinel. It is softer than corundum because of the admixture of the magnetite and spinel. It is used as an abrasive for special purposes.

In the United States spinel emery occurs at Peekskill, New York, at Chester, Massachusetts, and at Whittles, Virginia, in large quantity, but most of that produced during 1927 came from Peekskill. At this place the emery is an original segregation[8] of basic oxides in the magma of a norite, or is the result of the absorption of sillimanite by this and other magmas that formed the basic rocks of the region.[9] The masses may consist of 50% corundum, or of 100% spinel, or the accompanying magnetite may be in such great quantity as to constitute an iron ore:

TABLE LVI.—ANALYSES OF SAMPLES OF EMERY FROM PEEKSKILL, N. Y.

	Al_2O_3	Fe_2O_3	MgO	Fe_3O_4	Other
I	38.78	24.35	7.92	17.37	11.83
II	46.53	32.31	9.43	8.98	2.95

The Chester occurrence is a vein from a few feet to 12 feet wide and 5 miles long. It follows the foliation of a hornblende schist. The emery is in pockets surrounded by chlorite. The occurrence probably represents a dike of peridotite.

The Whittles deposit of spinel emery is in lenses near the contact of schist and granite. It is believed to be the result of contact action.[10] Tests made by the U. S. Bureau of Mines show that it is of better quality than the Peekskill product and nearly equal to that from Turkey.

[8] Williams, G. H., "The Norites of the 'Cortlandt Series' on the Hudson River, Near Peekskill, New York," *Amer. Jour. of Sci.* 3, Vol. 33, pp. 191–199, 1887.

[9] Rogers, G. S., "Geology of the Cortlandt Series and Its Emery Deposits," New York Acad. of Sci., *Ann.* Vol. 21, pp. 11–86, 1911.

[10] Watson, T. L., "A Contribution to the Geology of the Virginia Emery Deposits," *Econ. Geol.*, Vol. 18, pp. 53–76, 1923.

Spinel emery occurs also in basic dikes in the peridotite areas of Macon County, North Carolina. Some of them were worked during the World War.[11] This emery differs from that in Virginia in containing considerable rutile.

The domestic production of emery is small. In 1927 it amounted to 506 short tons valued at $5,855. In 1917, however, about 17,000 tons were produced with a value of $241,000. All was of the spinel type.

Nearly all the emery used in the United States is imported from Asiatic Turkey and Greece as ballast. In both countries it occurs in large quantity on the islands in the Ægean Sea, of which the Isle of Naxos is the best known, and on the adjoining mainland near Smyrna in Asia Minor. The emery, which contains very little, if any, spinel, is in a metamorphosed limestone that is associated with mica schists and gneisses. It occurs in pockets several hundred feet in diameter scattered irregularly through the limestone.

The imports of corundum and emery during the past few years have fluctuated between $264,613 and $723,000 annually. In 1927 they were valued at the lower figure.

Artificial abrasives.—The artificially prepared abrasives which are in competition with corundum and emery are:

Crushed Steel Carborundum Crystolon Carbolon	Silicon carbide.
Alundum Aloxite Exolon Lionite Coralox Natite	Aluminium oxide.

[11] Bayley, W. S., "The Magnetic Iron Ores of East Tennessee and Western North Carolina," Tenn. Division of Geol., *Bull.* 29, pp. 225–226, 1923.

The production in 1927 of all these was 90,623 short tons valued at about $7,959,891, of which 26,289 tons, valued at $2,603,571 were silicon carbide and 50,973 tons valued at $4,516,637 were aluminium oxide.

GARNET

Garnet is employed as a gem and as an abrasive in the wood-working, leather and plate-glass industries. The gem garnets (almandite, pyrope and spessartite) are all crystallizations from magmas. Those used for abrasives are mainly metamorphic products.

Although India is the main source of supply of gem garnets, they are known to occur at many places in the United States. They are, however, produced only in Arizona and New Mexico, where they are collected by the Indians to the value of about $1,500 annually. The garnets lie in sands near the Utah-Arizona line, near San Juan River. In this region the underlying rock is a Triassic sandstone cut by numerous basic dikes in which the garnets occur. When the rocks weather the sandstone breaks down into sand and the dike material disintegrates, freeing the garnets from their matrix. The stones measure on the average about 12 millimeters in diameter, though many have diameters of 3 centimeters. A purple-red garnet rhodolite [12] is found in Macon County, North Carolina. A few rhodolites have been used as gems.

The commonest abrasive garnets are almandite ($Fe_3Al_2(SiO_4)_3$) and grossularite ($Ca_3Al_2(SiO_4)_3$), since only these occur in large enough quantity to be mined cheaply. The best material is coarsely crystallized and free from hornblende, chlorite, mica and pyroxene, all of which are comparatively soft, and easily broken down because of their

[12] Kunz, G. F., "History of the Gems Found in North Carolina," N. C. Geol. and Econ. Sur., *Bull.* 12, pp. 49–51, 1907.

ready cleavage. In most cases the mineral, where in large quantity, is a product of metamorphism of limestones or other sediments by igneous rocks, but in North Carolina it occurs as a constituent of a biotite-quartz schist which is probably a product of dynamic metamorphism, and in Canada as a component of hornblendic and micaceous schists and gneisses.

Most of the abrasive garnet produced in the United States comes from the Adirondacks,[13] where are situated the largest garnet mines in the world. The garnet occurs as crystals or grains in gneisses that are metamorphosed sediments; as crystals in intrusive rocks, and as large masses enclosed in lens-like inclusions of hornblende gneiss in granites. The garnets form 7% or 8% of the rock, which is quarried and crushed and then passed over jigs or other separators.

In New Hampshire a mass composed of garnet, biotite, quartz and albite is quarried and concentrated. The garnet forms 60% of the rock but work cannot be undertaken on the large scale practiced in New York and consequently the cost of production of the finished product is greater.[14]

The mineral occurs in large quantity also at many other places, but it has been mined only in small quantity at Sugar Loaf Mountain, near Willets in North Carolina, where it constitutes about 25% of the mass of a biotite-quartz schist.

Some garnet has been imported from Spain where it is obtained by washing sands, but the quantity is inconsiderable, and from Canada where it was obtained from a deposit near Bancroft, Ontario.

[13] Miller, W. J., "The Garnet Deposits of Warren County, New York," *Econ. Geol.*, Vol. 7, pp. 493–501, 1912.

[14] Myers, W. M., and Anderson, C. O., "Garnet. Its Mining, Milling, and Utilization," U. S. Bur. of Mines, *Bull.* 256, 1925.

Other countries than the United States, Canada and Spain produce abrasive garnet only sporadically.[15]

In 1927 the production of abrasive garnet in the United States was 6,939 tons valued at $573,525. There were no imports. There are no figures available to show the production and imports of gem garnets, but in 1919 the imports of precious garnet were valued at $1,630.

QUARTZ

Crystallized quartz that is transparent and varieties that are translucent and colored are used as gems. (See p. 330.) Vein quartz and that separated from pegmatites is known to the trade as flint. Flint is used mainly in making pottery, in metallurgical and chemical processes, as an adulterant in paints, as a filler for wood, in the manufacture of silica glass and as an abrasive in scouring soaps, in making sand-paper and in the manufacture of polishing powders. In the form of sand, quartz is employed extensively in making glass (p. 356). Quartz pebbles are used for grinding. Sandstone, grit and conglomerate are employed as linings for tube mills and in the manufacture of grinding and crushing wheels.

Within the last few years quartz has found a new use in the manufacture of quartz glass, which is noted for its ability to stand extreme changes of temperature without fracturing and to transmit ultra-violet rays, to which ordinary glass is opaque. Moreover, its index of refraction is so high and its transparency so perfect that light may be conducted around bends in rods with almost no loss of intensity, so that violet light from a mercury arc may be applied easily by surgeons through a bent quartz glass rod to points that are inaccessible to straight rays.

[15] Eardley-Wilmot, V. L., "Abrasives. Pt. III. Garnet," Can. Dept. of Mines, Mines Br., *Pub.* 677, 1927.

As an abrasive crushed vein quartz is preferable to sand or crushed sandstone because it has sharp edges. For the same reason it is preferred for paints and as woodfiller, because grains with sharp edges adhere more closely than those with rounded edges. For many other purposes crushed pure quartz sand and sandstone yield a product as desirable as that produced by crushing vein quartz.

The "pebbles" used in tube mills in the United States for grinding ores, cement and other hard materials are mainly quartz pebbles obtained from the beaches near San Diego, California, and cut cubes and artificially rounded blocks made from quartzite in Minnesota, Nevada, Iowa and South Dakota, although granite and other rock pebbles are used to a small extent. The tubes in which the grinding is effected are lined with quartzite blocks to protect them from abrasion.

Before the war pebbles were imported to the value of $320,000, mainly from Denmark, France and Belgium, and there was no domestic production, but after hostilities began the imports fell off until in 1918 they were valued at only $127,808, the domestic materials taking their place. In 1927 the production of pebbles and flint lining in the United States was 3,342 short tons valued at $46,856. The imports were valued at $93,658, mainly from France, Denmark and Belgium.

The "Danish" flint pebbles come from Greenland and the French flint pebbles from the coast between Havre and St. Valery-sur-Somme. "Flint pebbles" are also obtained in Germany, Italy, Labrador, Newfoundland and Japan.[16]

Granite pebbles suitable for use in tube mills occur in large quantity in Canada near Jackfish on the north

[16] Eardley-Wilmot, V. L., "Abrasives. Pt. I. Siliceous Abrasives," Can. Dept. of Mines, Mines Br., *Pub.* 673, pp. 49–50, 1927.

shore of Lake Superior, and rhyolite, quartzite, porphyry and andesite pebbles on the shore of Gabarus Bay, Nova Scotia.

The production of crude, crushed and ground quartz by original producers in the United States during 1926 was 27,743 short tons valued at $274,333, and of ground sand and sandstone 270,468 tons, valued at $1,928,793. Most of the quartz came from California, Maryland, Massachusetts and Wisconsin. The sand and sandstone were crushed in Illinois, New Jersey, North Carolina, Pennsylvania, Virginia and West Virginia. What proportions were used in the abrasive, ceramic, metallurgical, chemical and other industries has not been disclosed.

INFUSORIAL EARTH

Diatoms and radiolaria, and to a smaller extent sponges and a few other organisms, secrete silica. The animals

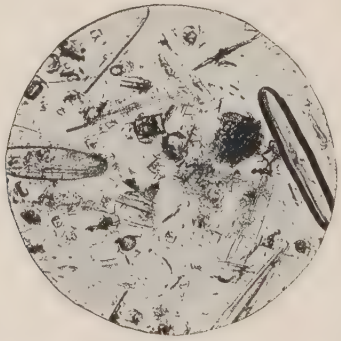


FIG. 106.—Microphotograph of diatomaceous earth (diatomite) from Simon Lake, Quebec. x 200. (*Courtesy of V. L. Eardley-Wilmot, Mines Br., Can. Dept. of Mines, Ottawa.*)

and plants live in the water of the ocean and of some lakes. When they die their hard parts drop to the bottom and form a great accumulation of ooze. When leached and compacted the ooze becomes infusorial earth, or if

the deposit consists principally of diatoms, diatomite, it is known as diatomaceous earth, or kieselguhr (Fig. 106).

Often the material is pure and white, consisting mainly of silica (opal) and traces of clay. More frequently, however, it is light-gray or brown or black. It is fine-grained and friable, and when white is distinguished best from chalk by the lack of effervescence with HCl, and from other apparently similar substances by microscopic appearance.

Analyses of radiolarian and diatomaceous oozes and a few types of infusorial earth are shown in the following table.

Infusorial earth occurs as definite beds in young formations and is now being deposited on the bottoms of some ponds and in marshes. The best-known deposits of diatomaceous earth are in California, where it occurs in thick, compact beds of marine origin.

TABLE LVII.—COMPOSITION OF SILICEOUS OOZES AND INFUSORIAL EARTH

	Ignition.	SiO_2	Al_2O_3	Fe_2O_3	MnO_2	CaO	MgO	$CaCO_3$	$MgCO_3$	$Ca_3(PO_4)_2$	$CaSO_4$
I.....	7.41	56.02	10.52	14.99	3.23	.29	.25	3.89	1.50	1.39	.41
II.....	5.30	67.92	.55	.39	....	...	...	19.29	1.13	.41	.29
III.....	6.04	81.53	3.43	3.34	....	2.61	...	....	.....	.....	...
IV.....	5.13	86.92	4.27	...	....	1.60	Tr.	....	.....	.....	...

I. Radiolarian ooze.
II. Diatomaceous ooze. Contains also 4.72% of insoluble matter.
III. Infusorial earth. Pope's Creek, Md.
IV. Infusorial earth. Point Sal, Calif.

It is found in the Coast Ranges of California and near the coast in Oregon and Washington, at various places in Idaho, Utah and Nevada, and on the Atlantic Coastal plain of Maryland and Virginia, in Nova Scotia and at many other places in America and Europe. It also occurs on lake bottoms in New York and some of the New England States. Because of its hardness it is used as a polishing powder, because of its porosity as an absorbent

for fertilizer and nitroglycerine and as an insulator, and because of its chemical inertness as a filtering material. It is also employed in the manufacture of water glass, ultramarine, and as a filler for gutta-percha and sealing-wax, and is mixed with cement to make concrete.

In 1926 about 87,126 short tons were produced in the United States with a value of $1,081,564. The chief source of its production was California. There was a large output also from Oregon and small outputs from Washington, New York, Nevada, Maryland and New Hampshire. The imports were slight.

TRIPOLI

Tripoli is a mixture of quartz and opal produced by the weathering of chert, or perhaps of siliceous limestone. It is a white, fine-grained friable material always associated with limestone (Fig. 107). It is used as a wood-filler, in making paint, as an abrasive, as foundry facing, and in the manufacture of filter stones.

The best-known tripoli deposits are at Stella,[17] Missouri, in the adjacent portions of Alexander and Union counties Illinois,[18] in Ottawa County, Oklahoma,[19] and in Tennessee.[20]

Since the Missouri tripoli is composed of particles of spongy, globular clusters of distinctly doubly refracting quartz, whereas the Illinois material is composed of clusters of crypto-crystalline silica, the latter is often known in the trade as amorphous silica. The Illinois material is thought to be a decomposition product of

[17] Siebenthal, C. E., and Mesler, R. D., "Tripoli Deposits Near Seneca, Missouri." U. S. Geol. Sur., *Bull.* 340, pp. 429–437, 1908, and Nelson, G., "Tripoli Deposits of Seneca, Missouri," *Min. World*, Vol. 31, p. 544, 1909.

[18] Barrett, N. O., "Mineral Resources of Illinois in 1916," State Geol. Sur. (Ill.), *Bull.* 36, pp. 59–61, 1920.

[19] Perry, E. S., "Tripoli Deposits of Oklahoma," Okla. Geol. Sur., *Bull.* 28, 1917.

[20] Glenn, L. C., "The Tripoli Deposits of Tennessee," *Science*, N. S., Vol. 39, p. 403, 1914.

cherts associated with Devonian limestones and the Missouri material a decomposition product of novaculite.

The production in 1926 was 31,369 short tons (including a small amount of rottenstone (see p. 354) produced in Pennsylvania), valued at $523,609, of which $65,002 was the estimated value of crude material sold. In 1927 the total tonnage produced was 26,099, valued at $447,068.

Of the amount produced in 1926 Illinois furnished 11,948 tons and Missouri, Oklahoma, Pennsylvania and Tennessee 19,421 tons. The Illinois product was valued at $192,483 and that from the other States $331,126. Most of the product was ground.[21]

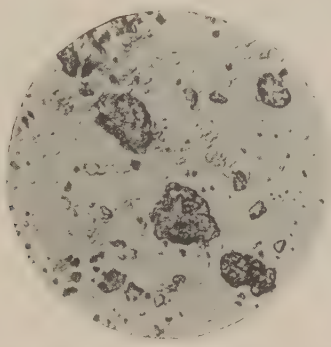


FIG. 107.—Microphotograph of amorphous silica (tripoli) from Murphresboro, Illinois. x 200. (*Courtesy of V. L. Eardley-Wilmot, Mines Br., Can. Dept. of Mines, Ottawa.*)

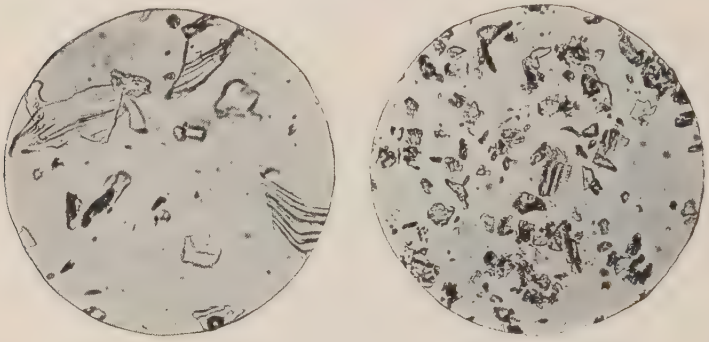
PUMICE AND PUMICITE

Pumice is a cellular, glassy, usually rhyolitic lava, made porous by the expansion of steam and gases escaping from the molten magma. Pumicite is a volcanic ash or dust consisting of small sharp grains of glass, formed by volcanic explosions (Fig. 108). Both materials occur widely spread in many volcanic districts but only a few deposits of

[21] See also Eardley-Wilmot, V. L., "Abrasives. Pt. I. Siliceous Abrasives," Can. Dept. of Mines, Mines Br., *Pub.* 673, pp. 70–77, 1927.

pumice have the physical properties demanded of high-grade material.

The best pumice is obtained from the island of Lipari, off the coast of Italy, and the greater part of it comes from a small area in the northeast part of the island.[22] Most of the pumice is ground before use. During 1927



A B

FIG. 108.—Microphotograph of volcanic dust (pumicite). A, from Caroll's Landing, Arrow Lakes, British Columbia. B, from Webb, Saskatchewan, Can. (*Courtesy of V. L. Eardley-Wilmot, Mines Br., Can. Dept. of Mines, Ottawa.*)

a small production of lump pumice was made in Imperial Valley, California.

Pumicite is obtained in Nebraska[23] and Kansas, though other large deposits are known also in the western States, in Alaska, in Canada, in Mexico and in New Zealand.[24] The material occurs in beds from a few inches to 100 feet thick, usually under a cover of loess (Fig. 109). Some deposits consist solely of glass particles, but in others there is an admixture of silt. The purer material was

[22] Ladoo, R. B., "Italian Pumice Industry," *Cement Mill and Quarry*, Sept. 5, 1920, p. 28.

[23] Barbour, E. H., "Nebraska Pumicite," Neb. Geol. Sur., Vol. 4, Pt. 27, pp. 357–401, 1916.

[24] Henderson and Ongley, "Pumice in New Zealand," Geol. Sur., N. Z., *Bull.* 21, pp. 41, 54, 74, 81, 1920.

deposited from the air, and the less pure was transported and deposited from water.

In 1926 the production of pumice in Italy amounted to about 45,000 metric tons and of pumice and pumicite in

FIG. 109.—Washout on side of Gun Creek, near Bridge River, B. C., Can. Shows at the top of the left side of the ravine a layer of andesite pumice, overlain and underlain by marl. *(Courtesy of V. L. Eardley-Wilmot, Mines Br., Can. Dept. of Mines, Pub. 673.)*

the United States 48,885 tons, and in New Zealand about 2,500 tons.

Block pumice is used for smoothing and polishing metals and wood, and to a small extent as a light-weight concrete aggregate.

Ground pumice is used in scouring and cleansing compounds, in tooth pastes and as an abrasive and polisher.

Pumicite is employed for the same purposes as ground pumice. It is the principal ingredient of many cleansing compounds, of abrasive hand soaps, of metal polishes, and is employed as a filler for paint and as an ingredient in concrete, taking the place of a considerable part of the cement.[25]

The total quantity of pumice and pumicite used or sold by producers in the United States during 1927 was 53,298 short tons, valued at $221,481. The imports of pumice were valued at $124,074.

ROTTENSTONE

Rottenstone is essentially a leached fine-grained siliceous calcareous shale, the greater part of which is argillaceous material. Small quantities are produced in Lycoming County, Pennsylvania, and in England, Wales and Belgium. It is a soft abrasive used for polishing wood and metal. Most of the rottenstone used in the United States is imported.

SAND, GRIT AND CONGLOMERATE

Consolidated sand, or sandstone, and conglomerate have a use as abrasives of special types. These are classified as millstones and burrstones, grindstones and pulpstones, oilstones, hones and scythestones.

Millstones of various kinds produced and sold in the United States during 1927 were valued at $35,438. They came mainly from Ulster County, New York, and Montgomery County, Virginia. Most of them are made from quartzite and conglomerate, but a few are cut from granite,

[25] Eardley-Wilmot, V. L., "Abrasives. Pt. I. Siliceous Abrasives," Can. Dept. Mines, Mines Br., *Pub.* 673, pp. 80–94, 1927.

particularly in Maine, Minnesota, New Hampshire and North Carolina. Imports were valued at $12,726.

Grindstones and pulpstones were produced in 1927 in Ohio, West Virginia, Michigan and Washington. All were made from sandstone. The total production consisted of 25,929 pieces valued at $1,554,750. The imports were valued at $134,803.

The largest producers of grinding stones outside of the United States are Canada, France, Bavaria, Belgium and Italy.

Oilstones, whetstones, hones, scythestones and rubbing stones were produced in 1927 to the value of $233,545. Oilstones were made from the novaculite at Hot Springs, Arkansas, whetstones chiefly from sandstones in Indiana and Kentucky, scythestones from sandstone in Indiana and Ohio, and from schists in New Hampshire and Vermont, and rubbing stones from sandstone in Indiana, Ohio and Washington. Whetstones and oilstones made up the greater portion of the production, and nearly all of the latter came from Arkansas.[25] In 1927 ironstone (iron carbonate) from Blue Mountain, Mississippi, was made into satisfactory finishing hones, but not in commercial quantity.

The imports of whetstones, oilstones and hones during 1925 were valued at $67,068.

The largest producing centers for whetstones, hones, and oilstones are England, Scotland, Wales, Belgium, Germany and Asia Minor.

For the past score of years the natural oilstones, whetstones, hones, etc., have had to meet the competition of the artificial stones made from carborundum, alundum and similar substances.

[25] For a comprehensive discussion of grinding and cutting stones, see Eardley-Wilmot, "Abrasives. Pt. I. Siliceous Abrasives," Can. Dept. of Mines, Mines Br., *Pub.* 673, pp. 1–48 and 51–64, 1927.

CHAPTER XII

SAND AND GRAVEL

The distinction between coarse sand and fine gravel is not sharp. Sand may be defined as a naturally occurring, incoherent, granular mass of mineral grains with diameters between .05 and 2.4 millimeters. A collection of particles with diameters greater than 2.4 millimeters and less than 10 millimeters is gravel.

Sand deposits may be laid down in streams, lakes or the ocean, or by the wind. Alluvial and marine deposits are usually more satisfactory for commercial purposes than lake deposits because better sorted. Eolian sands occur in dunes, but because their grains are unusually fine and are often rounded they are not as valuable for some purposes as are the marine and stream deposits.

Gravel is accumulated mainly in the beds of streams or in the moraines of glaciers. Since much gravel is mixed with sand it must be sifted before use.

SAND

Glass sand.—Pure quartz sand is used as a source of SiO_2 in the manufacture of glass. For this purpose the sand must be nearly pure quartz as the presence of impurities vitiates the batch. Iron compounds impart a green color to the glass, clay causes cloudiness and magnesia renders the mixture less fusible. Therefore, glass sand should be thoroughly washed before using. Some of the river sands are pure enough to be used without further washing, since they have already been cleaned by the current of the streams in which they are found. The

best sands have a uniform grain, which ranges between 30 and 120 mesh.[1]

Most of the quartz used in glass manufacture comes from sandstones which, however, are nothing but sands consolidated into rock. The sandstones are crushed and washed and then sifted. The sandstone used may be of any age from the Ordovician (in Illinois) to the Tertiary (in New Jersey).

The quantity of sand produced by suction from rivers is not known, but it is large.

The total quantity of glass sand produced in the U. S. in 1927 was 2,171,693 tons valued at $3,257,790. The principal producing States and the values of the production in each State are shown in the following table.

TABLE LVIII.—PRODUCTION IN SHORT TONS AND VALUE OF GLASS SANDS FROM CERTAIN STATES (1927)

West Virginia	509,905	$1,100,413
Pennsylvania	423,895	814,013
Illinois	629,268	356,333
New Jersey	185,568	278,588

Molding sand.—Sand is used also for making molds and cores in foundries. Such sands must possess: (1) enough binding material to make them cohere, (2) sufficient refractoriness to resist fusion, (3) proper texture, fine for small castings, coarse for large ones, (4) sufficient porosity when made up to allow of the escape of gases, and (5) durability.[2]

Molding sands are obtained from many points east of the Mississippi River—usually from surface formations, but at some places from Cretaceous and Tertiary deposits.

The output of molding sands in 1927 was 4,194,975

[1] Burchard, E. F., "Glass Sand, Other Sand and Gravel," U. S. Geol. Sur., *Min. Res., 1911*, Pt. II, pp. 593–635, 1912.

[2] Stone, R. W., "Sand and Gravel," U. S. Geol. Sur., *Min. Res. for 1912*. Pt. II, pp. 632–4, 1913.

TABLE LIX.—MECHANICAL ANALYSES OF FOUNDRY SANDS
(Caught on sieves with meshes as indicated)

	20	60	100	250	*Clay*	*Per Cent Pore Space*
1.....	6.84	46.7	32.8	12.56	1.06	36.2
2.....	4.69	37.3	16.96	18.22	22.79	45.0
3.....	.40	72.78	10.80	2.60	13.34	40.41
4.....	.96	36.83	11.81	18.29	22.06	38.8
5.....	42.48	19.06	2.55	8.58	26.44	.....

1. Fine core sand, Jackson, Mich.
2. Core sand, Niles, Mich.
3. Core sand for heavy castings, Janesville, Wis.
4. Sand for general work, Zanesville, Ohio.
5. Coarse sand, Richmond, Va.

tons, valued at about $4,458,508. Ohio, Illinois, New York, Michigan, Pennsylvania, New Jersey and Indiana were the principal producers.

Filter sand.—Filter sand is clean sand in sorted sizes that may be used for beds in water filtration plants and small mechanical filters.

The annual production is about 75,000 tons, valued at about $155,000.

New Jersey was the principal producer in 1927.

Sand for other purposes.—Sand is used also for building, for paving, for use in furnaces, in engines, for railroad ballast, as an abrasive, and for many other purposes.

Besides the sand used for the above-named purposes there was considerable employed in the manufacture of sand-lime and silica brick, of which about 330,586 thousands were sold at $3,981,492, and a still larger quantity used on roads and in concrete. No records of these quantities are available.

PRODUCTION

The total of all sand produced in the United States during 1927 was 93,588,339 short tons, valued at $54,291,-

398, of which New York, Illinois and Pennsylvania each produced over 9,000,000 tons. The imports were 422,000 tons valued at $198,000, mostly from Canada.[3]

In addition 275,373 tons of sand and crushed sandstone with a value of $1,897,303 were sold for use in pottery, scouring soaps, wood fillers, paint, as a flux, as an abrasive, as a filler of filters, and in making alloys of silicon with iron, copper, etc.

GRAVEL

The total amount of gravel produced in 1927 was 103,865,930 short tons valued at $61,238,388, of which about 30,500,000 tons were used for building, about 44,900,000 tons for paving and 30,000,000 tons for railroad ballast.

The largest producers of gravel were Michigan, Illinois, Indiana, California, New York and Ohio, each with a production of over 7,000,000 tons, most of which comes from glacial deposits. The New York and Michigan outputs had values of more than $5,000,000 each.

The imports of gravel were 313,809 short tons valued at about $104,000. Most of this came from Canada and Belgium as ballast.

The exports of sand and gravel in 1927 were 421,243 short tons valued at $557,644.

[3] The most thorough discussion of sand and crushed rocks and their uses will be found in *Sands and Crushed Rocks*, by A. B. Searle, 2 vols., 1923.

CHAPTER XIII

CERAMIC MATERIALS

The principal substances used in the ceramic industry are quartz, feldspar and aluminous materials of which the most important is clay. For porcelain and some other products certain aluminous minerals such as bauxite, andalusite, etc. (pp. 375–384), are preferred to clay, because they contain fewer undesirable constituents. Quartz has already been briefly discussed on pages 330 and 346. In the manufacture of brick, terra cotta, stoneware, earthenware, etc., only clay is needed, but for the making of whiteware and porcelain, quartz and feldspar are mixed with kaolin or pure clays in order to secure a more compact product. The feldspar is the flux, the kaolin furnishes alumina to form aluminous crystals that serve as a binder and strengthener, and the quartz forms the main part of the body of the ware and prevents excessive shrinking during burning. The alumina combines with some of the silica at the high temperature produced in the kiln and forms acicular crystals of mullite ($Al(AlO)_5(SiO_4)_2$) which interlock and aid in making the ware rigid and elastic. For enamels and glazes more feldspar is used than in whiteware because these products must contain a large proportion of glass in order that they may be translucent.

Zirconium compounds are also used in the manufacture of ceramic products, especially in the making of refractory materials, but it is employed also for other purposes as well. At present it is not of great economic importance, but its use is rapidly expanding. (See p. 384.)

CLAY

GENERAL PROPERTIES

Clays are mixtures of kaolinite, halloysite, montmorillonite, other platy minerals, various colloidal substances like gelatinous silica, quartz, remnants of undecomposed minerals, etc., which owe their value to their plasticity and the fact that they burn to a hard stony product. Their color and the uses to which they may be put depend upon the nature and physical characters of their components. They may be residual or sedimentary and the latter may be marine, lacustrine, estuarine or valley clays. The residual clays are usually designated as kaolin.

TABLE LX. ANALYSES OF TYPICAL CLAYS

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	TiO_2	P_2O_5	H_2O+	H_2O-	MnO	TOTAL
1...	46.95	37.24	.40	Tr.	Tr.	.24	.49	.05	..	14.10	....	...	99.47
2...	44.23	38.92	2.31	.12	Tr.	.26	.30	1.21	..	12.90	....	...	100.25
3...	44.85	33.15	2.04	.30	.42	.10	.66	.03	..	18.45	....	...	100.00
4...	55.21	31.18	.07	.18	.11	...	.23	...	..	13.02	.23	...	100.23
5...	56.44	26.60	2.00	.47	.63	.26	3.20	...	..	7.57	2.48	...	99.65
6...	55.60	14.80	5.80	5.70	2.48	1.07	3.23	...	.15	5.18	4.94a	.14	98.09

a. Includes some CO_2

1. Washed kaolin, Bryson, N. C.
2. Paper clay, "Sedimentary kaolin." Immaculate Kaolin Co., Langley, S. C.
3. Ball clay, Whitlock, Tenn.
4. Fire clay, Somerset Co., Pa.
5. Stoneware clay, Steubenville, Ohio.
6. Albany slip clay, Albany, N. Y.

The chemical properties of clays affect largely their behavior during burning. Some of their constituents like calcium, magnesium and the alkalies are fluxes. Aluminium and silicon are refractories. Calcium carbonate is a bleacher. Iron is a producer of color. If iron is present without calcium the clay will burn dark-buff or red depending upon its quantity. If calcium is present in large quantity the burnt clay will be cream or light-buff.

The physical properties of importance, which in turn depend upon chemical and mineral composition, but in

such a way that they cannot be predicted but must be determined, are plasticity, tensile strength, shrinkage, fusibility and specific gravity. Plasticity depends in large measure upon the quantity of very small fibrous and platy minerals present in the clay.

VARIETIES

The most practical classification of clays is that based on their uses. The United States Geological Survey distinguishes between kaolin; china and paper clay; slip clay; ball clay; fire clay; stoneware clay; brick clay; sewer pipe and terra-cotta clays.

KAOLIN.—Kaolin is a white residual clay composed of a mixture of kaolinite ($H_4Al_2Si_2O_9$) and other substances produced by the weathering of feldspathic rocks, or by the action upon them of magmatic gases. Kaolin possesses very slight plasticity. It is used for making porcelain, china, whiteware and high-grade tile. Pure kaolinite fuses at about 1850° C.

At places where the kaolin is the product of weathering, the alteration, which is the result of the action of the CO_2 of the atmosphere, ceases at or just below the level of ground water, and below this level unweathered rock is reached. In the deposits made by pneumatolytic action, there is no definite relation between the depth of alteration and the ground-water table. The deposits are usually similar vertically for considerable distances and fade out laterally. The best kaolins are those made by the alteration of the feldspars of pegmatites and granites,[1] though they may result also from the alteration of feldspathic schists and other rocks.

The kaolins made from pegmatites naturally occur in vein-like sheets intersecting rocks of every kind (Fig. 110).

[1] Bayley, W. S., "Kaolin in North Carolina," *Econ. Geol.*, Vol. 15, pp. 236–246, 1920.

Those made from granitic and other feldspathic igneous or sedimentary rocks occur in blanket deposits extending over broad areas. In either case the resulting kaolin is a mass of kaolinite and other platy minerals, quartz, mica and the alteration products of any of the other components of the original rocks. It must be refined by washing and settling in currents of water. The final settling is in tanks, from

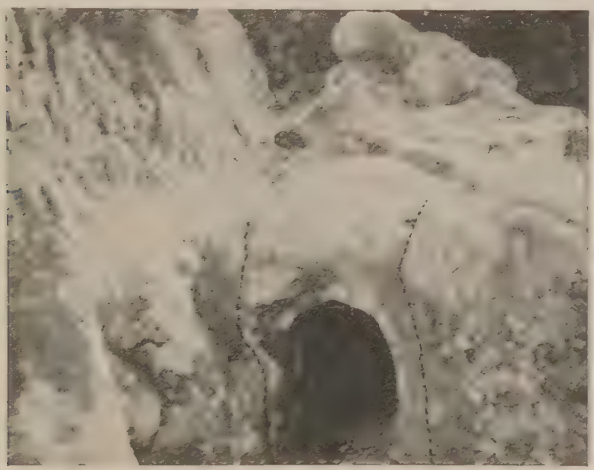


FIG. 110.—Tunnel in kaolin mass resulting from the weathering of a pegmatite dike. The dike is enclosed between the dotted lines. Payne and Sullivan Mine, Bryson, N. C.

which the refined kaolin is pumped into filter presses and compressed. When dry the "cakes" are ready for shipment.[2]

The alteration of the feldspar to kaolinite by weathering takes place approximately as indicated by the equation below, though the reaction may occur in several stages.

$$2KAlSi_3O_8 + 2H_2O + CO_2 = H_4Al_2Si_2O_9 + 4SiO_2 + K_2CO_3$$

Much of the SiO_2 and all of the potassium carbonate are removed in solution leaving the kaolinite behind with the unaltered substances. Since carbon dioxide seems to be

[2] Watts, A. S., "Mining and Treatment of Feldspar and Kaolin in the Southern Appalachian Region," U. S. Bur. of Mines, *Bull.* 53, 1913.

necessary to the process kaolin should be abundant under swamps and moors. Indeed, many blanket deposits are under the sites of old marshes, and under many modern ones kaolin is now forming.

The kaolin now produced in the United States comes mainly from weathered pegmatites in the mountains of North Carolina and in the Piedmont plateau in the same State. It is used in the ceramic industry for making porcelain and whiteware.

Kaolin of a similar origin occurs in Delaware and Chester counties, Pennsylvania, and in the northern part of Delaware, and clays that are similar to kaolin in their properties but which are different in origin occur in Pennsylvania, Connecticut, Virginia, California, Indiana and a few other States. Some are derived by the weathering of Cambrian schists, quartzites and shales, others by the weathering of limestones and calcareous shales. The kaolin in Maryland is derived from a granodiorite. Indianite, which lies near the contact between the Mississippian and Pennsylvanian rocks in Indiana, is a coarsely granular, a concretionary or a porcelain-like white or light-green clay that is thought by Logan [3] and Ries to have been formed by the action of aluminium sulphate on the quartz of the Pottsville sandstone. The aluminium sulphate is believed by Ries to be due to the action of sulphuric acid on shales, but Logan ascribes it to the action of bacteria. A very small quantity of these clays is employed in making whiteware.

In 1927, 20,334 short tons of kaolin, valued at $327,638, were produced from North Carolina. It was all used in making porcelain and china.

This was in competition with imports of china clay (mainly kaolin) from England amounting to 339,014 tons

[3] Logan, W. N., "Kaolin of Indiana," Indiana Dept. of Conserv., *Pub.* 6, pp. 35–76, 1919.

valued at $2,937,113. Not all of the imported clay, however, was employed in china-making, some of it being used as paper filler.

China and paper clay.—China and paper clay is a white, fine-grained, plastic, sedimentary clay that is uniform in texture. In statistics it is usually included with kaolin. China clay is used in making china and white-

Fig. 111.—Bed of paper clay 15 ft. thick. South Carolina Clay Co., Langley, S. C. The clay is overlain by beds of sand and interlaminated thin beds of sand and clay.

ware in general. It must be free from iron and burn white or light cream-colored. Paper clay must be smooth, free from grit, must disintegrate when moistened and must be exceeding fine-grained. China and paper clays occur in beds 10 to 12 feet thick, often interstratified with colored layers. Most of the sedimentary white clay produced in the United States comes from Upper Cretaceous and Tertiary beds in South Carolina (Fig. 111), Georgia, Florida, Mississippi, Tennessee and Kentucky.[4]

[4] Ries, H., Bayley, W. S., and others, "High-grade Clays of the Eastern United States, with Notes on Some Western Clays," U. S. Geol. Sur., *Bull.* 708, 1922.

The quantity sold by producers in 1927 was 433,911 short tons valued at $3,482,196. Of this 193,151 tons came from Georgia, 78,401 tons from South Carolina, 75,939 tons from Pennsylvania, and 47,319 tons from Florida. About an equal quantity of china clay is imported annually from England.

Slip clay.—Slip clays contain a considerable amount of fluxing material. They fuse at a very low temperature, and form a low-shrinking glaze on more resistant bodies. Their main use is for glazing and as a binder in the manufacture of abrasives. The best comes from Albany, New York. In 1927 6,137 short tons were sold with a value of $32,264. It came from New York and Michigan.

Ball clay.—Ball clay is a very plastic white-burning clay used to give plasticity to other clays. It has a strong bonding power and is highly refractory. About 119,763 short tons were mined in 1927 having a value of $913,976. Most of it came from Tennessee and Kentucky.

Fire clay.—The fire clays are very resistant to heat. They are very slightly plastic and burn with little change except dehydration. Flint clay is a hard, dense, non-plastic, refractory clay with a conchoidal fracture like flint. The best fire clays are found under coal beds. They occur, however, at other horizons as well. In 1927, 2,699,761 short tons were sold at a value of $7,719,725. Fire clay is used in making furnace linings, refractory brick and crucibles, but large quantities are used also in sanitary ware, stoneware, cement, plaster, etc. In 1927 Pennsylvania, Missouri, Ohio, New Jersey, California, Colorado, Illinois and Indiana were the largest producers.

Stoneware and earthenware clays.—Stoneware clay is a very plastic clay of any color, burning at a low temperature to a dense or vitrified body, and possessing great tensile strength.

Earthenware clay is plastic, but it burns with an open texture.

Nearly all clay used in making stoneware and earthenware is produced by the manufacturers of the wares, the factories being placed on the sites of the pits, consequently the tonnage of the clay raised does not enter into the records. The earthenware manufactured annually is valued at about $2,400,000 and the stoneware at about $5,500,000. The quantity of stoneware clay sold in 1927 was 98,355 short tons valued at $203,648.

Miscellaneous clays.—Brick clays, terra-cotta clays, sewer-pipe clays, etc., vary widely in appearance and physical properties. They may be of any character, provided they burn at the proper temperature and yield the desired color and texture. Crushed shales of the proper composition may be used in place of clay in the making of terra-cotta, roofing tile and brick. The eastern brick clays yield a red brick, because they are derived from rocks that contain little or no calcium. The iron in them burns to hematite. In the Mississippi Valley most clays contain an abundance of lime and are cream-colored when burned.

The quantity of brick clay sold is always small, because most of it is dug by those who use it. The amount dug, however, must be very great since the annual production of bricks in the United States is about 6,200,000,000, and the annual value of brick, terra-cotta and tile is about $215,000,000.

PRODUCTION AND IMPORTS

The total value of all the clay sold in the United States during 1927 was about $14,000,000 and the tonnage about 3,900,000, but this represents only a comparatively small part of all the clay used.

The total imports of clay into the United States in 1927

were 394,500 tons valued at $3,448,970 and the exports 99,384 tons valued at $1,117,889. The greater part of the imports was china clay and of the exports fire clay.[5]

USES

The principal uses to which domestic clay was put in 1927 and the tonnage sold in that year were as follows:

Fire brick	956,364	Whiteware	143,472
Refractory linings	482,104	Terra-cotta	105,616
Fire clay mortar	463,375	Cement and plasters	85,567
Paper-filler	193,508	Stoneware	78,314
Saggers	165,052		

EUROPEAN OCCURRENCES

The best known deposits of clay in Europe are in southern England, near Limoges and Sevres in France, in Saxony, in southeast Bavaria and Thuringia, in Hesse and in several other districts in Germany, at Zettlitz, Karislinenthal and Budweis in Bohemia, on the island of Bornholm, Denmark, and in the Belforge and Ardennes districts in Belgium.

The English china clay deposits are regarded as the most important in the world because of the quality of the clay and the size of the deposits, which are probably residual. In south Devon are ball clays in stratified deposits of Tertiary age but the china clay of Cornwall is derived from granite and other crystalline rocks.[6] In 1927 the production of china clay was over 1,012,000 short tons and of ball clay a little over 60,000 tons.

BENTONITE

Recently the clay-like material bentonite, or Denver mud, has come into use in the manufacture of paper, soap

[5] Ries, H., *Clays; Their Occurrence, Properties and Uses.* 2nd Ed., 1927.
[6] Searle, A. B., *British Clays, Sands and Shales.* London, 1911.

and cosmetics, and as a substitute for Fuller's earth as a filter for oil. Mixed with glycerine it is known as antiphlogistine.

The rock consists of montmorillonite ($(Mg.Ca)O.Al_2O_3.5SiO_2 + nH_2O$) and other micaceous minerals that have resulted from the devitrification and chemical alteration of glassy volcanic ash or tuff, and remnants of undecomposed or only partially decomposed minerals that were originally embedded in the glass, together with variable quantities of sand.[7]

Analyses of selected crude bentonite from Maricopa, Kern County, California (I), and of purified bentonite from Wisconsin, Texas (II), are quoted below. In III is an analysis of montmorillonite.

TABLE LXI.—ANALYSES OF BENTONITE

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	H_2O	TOTAL
I.....	50.33	16.42	2.42	1.39	4.10	1.00	.12	23.95	99.85
II.....	52.08	18.20	2.88	2.28	4.48	...	...	20.80	100.72
III.....	48.60	20.03	1.25	1.72	5.24	MnO = .16		21.52	98.52

Bentonite is exceedingly fine-grained, is very plastic and has a waxy luster. It absorbs from 3 to 7 times its volume of water and expands more than 6 times its original volume. It is easily fusible at a low temperature. Some bentonite possesses the property of allowing easy replacement of its alkalies by alkaline earths and consequently may be used to soften hard water.

Only small quantities of bentonite are now being mined, principally in California, but it is known to occur fairly widely in beds from a fraction of an inch to 5 or 6 feet in

[7] Spence, H. S., "Bentonite; Feldspar," Can. Dept. Mines, Mines Br., *Inv. of Min. Res. and Mining Industry*, 1923, pp. 1–3, 1924.

Ross, C. S., and Shannon, E. V., "The Minerals of Bentonite and Related Clays and Their Physical Properties," Amer. Cer. Soc., *Jour.* Vol. 9, pp. 77–96, 1926.

thickness over the western and southern portions of the United States, in Mexico, western Canada, Alaska, China and probably elsewhere, and the prospect is fair that it will soon replace Fuller's earth and paper-clay for some purposes.

FULLER'S EARTH

Fuller's earth is a clay with a high absorbent power for many substances. It probably contains a greater quantity of colloidal material than ordinary clay. Carbonates injure the bleaching power of the earth. It is used for clarifying oil, greases, etc. Petroleum is filtered through it and vegetable oils boiled with it. The material is also used in the manufacture of some pigments, as a substitute for talcum powder, and in medicine as an antidote for alkaloid poisons and as a poultice.

Recently bentonite has been used for some of the purposes for which Fuller's earth has heretofore been used. After treatment with sulphuric acid, it is said to be superior to the earth.

The earth is instratified with sands or clays of the later geological formations in many States. It is dug at points in Georgia, Florida, Nevada, Arizona, Texas, Illinois, and Massachusetts, but most of it comes from the first three States. In 1928, the total production was 287,012 short tons valued at $3,895,991.

The importation during 1928 was about 7,592 tons, with a value of about $132,000 and the exportation about 16,494 tons.

Large deposits are known to exist in Germany.

FELDSPAR

COMPOSITION AND USES

Feldspar, or spar, is employed mainly in the ceramic industry and to a less extent as an abrasive in scouring

soaps and window washes. Very pure varieties are used in making artificial teeth. The lower grades are used as binders in the manufacture of emery and corundum wheels

FIG. 112.—Feldspar vein in schists. Frog Rock Mine, North State Feldspar Corp., Micaville, N. C. (*Courtesy of J. L. Stuckey, Univ. of N. C.*)

and in the manufacture of glass, roofing material and concrete. All of it comes from pegmatites (Fig. 112).[8]

A small quantity of translucent feldspar is used as a

[8] Bastin, E. S., "Economic Geology of the Feldspar Deposits of the United States," U. S. Geol. Sur., *Bull.* 420, 1910, and "Geology of the Pegmatites and Associated Rocks of Maine, Including Feldspar, Quartz, Mica and Gem Deposits," U. S. Geol. Sur., *Bull.* 445, 1911.

gem under the name moonstone, and translucent pieces containing spangles of iron oxide under the name sunstone. The aggregate value of all the gem feldspar produced in the United States is rarely more than $400.00 annually.

The consumption of feldspar in the United States at present is for the following uses: ceramic industries, 84%, roofing, etc., 6%, cement manufacture, 5%, in scouring soaps and powders, 2.5%, for binders in emery wheels, etc., 2%, for chicken grit 0.5%.

The feldspars consist of several series of minerals of which the potassium-barium and the sodium-calcium series—the latter known as plagioclases—are the most important. The nearly pure potassium compound occurs as two minerals—orthoclase and microcline—differing in crystallization. The nearly pure sodium type is albite. Those varieties are most valuable that contain least iron and therefore that are white in color. A few pink and yellow varieties, however, contain so little iron that they become white when calcined. Tourmaline, garnet, biotite and other dark impurities are particularly objectionable.

The value of the feldspars depends mainly upon the fact that they fuse to a stiff fluid at moderately low temperatures between 1310° C. and 1532° C. Since the alkaline varieties fuse at the lower temperature these are the most desirable for use.[9]

Most of the feldspar quarried in the United States contains both potassium and sodium but the purer sodium feldspar is also produced to some extent. In quarrying the mica and quartz which often accompany the feldspar are usually excluded, but the inclusion of small quantities of either in the marketed stock is not regarded as detri-

[9] See Geller, R. F., "Investigation of Feldspars. Second Progress Report," Amer. Cer. Soc., *Jour.*, Vol. 10, p. 411, 1927.

mental.[10] No. 1 spar should be practically free from quartz; No. 2 grade should contain less than 25% and No. 3 grade not over 30%.

A few analyses of the feldspars furnished to potteries are:

TABLE LXII.—COMPOSITION OF FELDSPARS USED IN POTTERIES

	SiO_2	Al_2O_3	Fe_2O_3	CaO	K_2O	Na_2O	MgO
I.....	65.96	19.53	.24	.18	12.92	1.13	....
II.....	64.62	20.57	Tr.	.14	1.94	10.27	2.36
III.....	63.50	22.39	.36	2.15	3.40	6.27	....

I. Potassium feldspar (microcline), Woodstock, Md.
II. Sosium feldspar (albite), Chester, Pa.
III. Potassium-sodium feldspar, Embreeville, Pa.

PRODUCTION AND IMPORTS

UNITED STATES.—The principal production of feldspar in the United States is from pegmatites in the Appalachian States (Fig. 113).[11] It is sold both crude and ground. The total quantity of crude feldspar produced

TABLE LXIII.—LIST OF THE MOST IMPORTANT PRODUCERS OF CRUDE FELDSPAR IN THE UNITED STATES DURING 1927

	Tons	*Value*
North Carolina.....	100,756	$612,214
Maine.....	34,328	299,386
New Hampshire.....	27,449	223,077
New York.....	12,020	96,446
Connecticut.....	6,123	43,319

[10] Galpin, S. L., "A Preliminary Report on the Feldspar and Mica Deposits of Georgia," Ga. Geol. Sur., *Bull.* 30, 1915; Watts, A. S., "Mining and Treatment of Feldspar and Kaolin in the Southern Appalachian Region," U. S. Bur. Mines, *Bull.* 53, 1913; Watts, A. S., "The Feldspars of the New England and North Appalachian States," U. S. Bur. Mines, *Bull.* 92, 1916.

[11] Stuckey, J. L., "Feldspar and Feldspar Production in North Carolina," *Manufacturers Record*, June 30, 1927.

and sold during 1927 was 202,497 long tons with a value of $1,424,755.

The ground feldspar sold by mills weighed 223,915 short tons and was valued at $3,564,141. Of this 29,243 tons, valued at $617,987, was ground Canadian spar and a little

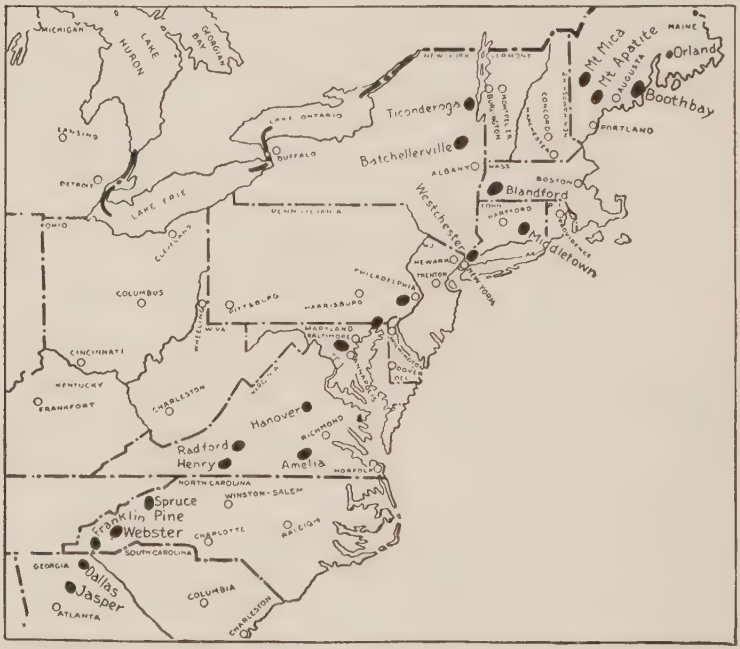


FIG. 113.—Important areas of feldspar occurrences in the Eastern United States. (*Courtesy of Manufacturer's Record, Baltimore.*)

Cornwall stone. Tennessee is the leading producer of domestic ground spar, with Maine and North Carolina following.

The imports of feldspar into the United States were nearly all from Canada and amounted to 27,604 long tons valued at $251,896, which is within a few hundred tons of the entire Canadian production.[12]

[12] De Schmid, H. S., "Feldspar in Canada," Can. Dept. of Mines, Mines Br., *Pub.* 401, 1916.

World.—In normal years before the war the production of feldspar in the United States was about one-third of that of the world, but since the beginning of the World War the output has greatly increased. In 1926 three-fifths of the world's production was in the United States. In this year the principal producers were:

	Metric Tons
United States	213,359
Canada	32,614
Sweden	33,970
Norway	20,510
Japan (1925)	19,049
Russia	18,640
Bavaria	6,660

CORNISH STONE

Cornish stone, or china stone, is used largely by the potteries in Great Britain in place of feldspar. It is a kaolinized granite rich in orthoclase and albite. Commercial varieties contain from 6.5 to 14.5% kaolin, 55.5 to 77% feldspar and 16 to 31% quartz. It is mined in conjunction with china clay in Cornwall, and is the principal source of the alumina used in the British pottery industry. A small amount was exported to the United States in 1927.

BAUXITE

Bauxite ($Al_2O(OH)_4$) is important principally as an ore of aluminium. It is employed also as a source of alumina in the manufacture of abrasives, refractories, cements and aluminous salts. High-grade aluminous refractories, containing at least 58% of Al_2O_3, are valuable because of their chemical inertness at high temperatures. Good bauxite brick will stand a temperature of 1800° C. High alumina cements are briefly discussed on page 410.

In order to be marketable bauxite should contain over

52% of Al_2O_3, though lower grade material if free from iron is acceptable to the manufacturers of refractories.

An approximate estimate of the quality of bauxite may be obtained by grinding a dried sample in an agate mortar for half a minute. A bauxite of good grade will be found hard to grind and will stick to the mortar with such tenacity that it will have to be scoured out, a poor bauxite or bauxitic clay will grind much more easily and will stick very little, if at all, and clay or kaolin will grind with ease and will not stick to the mortar.

OCCURRENCE AND ORIGIN

United States.—In nearly all places where it occurs bauxite gives evidence of having been produced from aluminous minerals by that process of weathering known as lateritization,[13] by which silica is extracted and aluminous and iron hydroxides are left on the surface.

In Alabama [14] the bauxite is found in an area 20 miles long and 10 miles wide in Tertiary beds on the Coastal Plain in Barbour and Henry counties, at an unconformity above the Clayton limestone. It is thought to represent old clay lenses that were exposed and altered by carbonic and humous acids. The Georgia deposits [15] in Sumter, Macon and Wilkinson counties are believed to have a similar origin. The larger deposits in northwestern Georgia are altered clay lenses in the Knox dolomite.

The Arkansas [16] deposits were formed by the weathering of a nepheline syenite which first changed to kaolin and then by loss of silica to bauxite (Fig. 114).

[13] Adams, G. I., "Bauxite Deposits of the Southern States," *Econ. Geol.*, Vol. 22, pp. 615–620, 1927.

[14] Rettger, R. E., "The Bauxite Deposits of Southeastern Alabama," *Econ. Geol.*, Vol. 20, pp. 671–686, 1925.

[15] Watson, T. L., "A Preliminary Report on the Bauxite Deposits of Georgia," Geol. Sur. of Ga., *Bull.* 11, 1904.

[16] Mead, W. J., "Occurrence and Origin of the Bauxite Deposits of Arkansas," *Econ. Geol.*, Vol. 10, pp. 28–54, 1915.

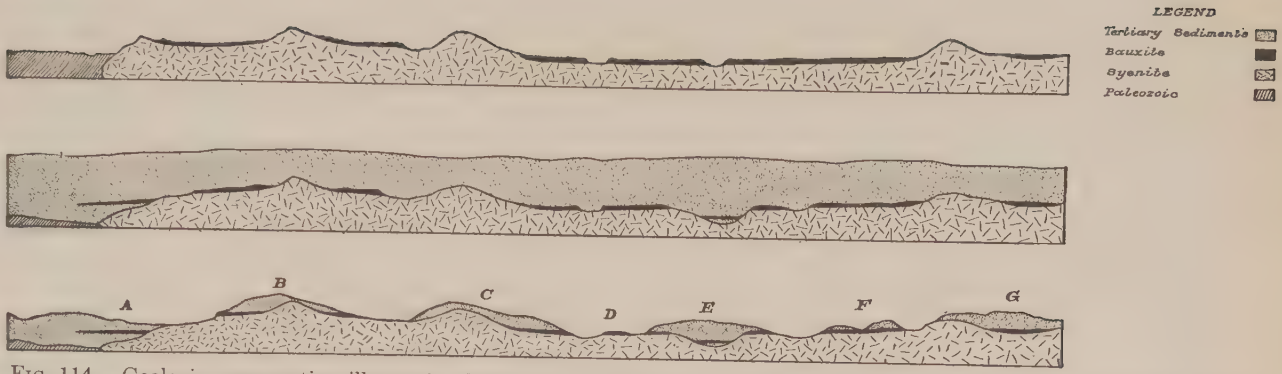


FIG. 114.—Geologic cross-section illustrating history of Arkansas bauxite deposits. (*After Mead, Economic Geology, Vol. 10.*)

Outside the United States.—Bauxite is known to occur in commercial quantities in the Gold Coast,[17] Nyasaland,[18] French Morocco, in Australia, in British and Dutch Guiana, in France, Germany, Hungary, Italy, Yugoslavia, Rumania, Russia, and elsewhere.

In Gold Coast the quantity of good ore available is estimated to be 26,500,000 tons, in Nyasaland 20,000,000 tons and in French Morocco 20,000,000 tons. In Hungary, north of Lake Balaton and in the Vertes Mountains deposits have been developed which are estimated to contain 30,000,000 metric tons of ore, and other deposits in the same general region increase this estimate to 200,000,000 tons. In Yugoslavia bauxite fields have been discovered in Dalmatia, Herzegovina and Montenegro, and those in Dalmatia are being worked energetically. In France some of the deposits which are near Baux, in Var, may be the stratified products of hot springs in a Cretaceous lake or estuary, but others are believed to be altered sedimentary rocks. In Italy the bauxite lies on the eroded surface of Upper Cretaceous or Lower Eocene limestones, where they are supposed to represent a residual deposit formed during an early Eocene erosion period. In Germany and Scotland the bauxite is believed to be a weathered product of basalt. In British Guiana it is the result of the weathering of porphyrites, pegmatites and other aluminous rocks. The deposits, some of which are very large, occur in the foothills along the Demerara and other rivers.[19] The most important at the

[17] Kitson, A. E., "Beauxite Deposits of the Gold Coast," *Mining Mag.* (London), Vol. 33, pp. 265–270, 1925, and Emory, L. T., "Bauxite on the Gold Coast," *Eng. and Min. Jour.-Press*, Vol. 121, Mar. 13, 1926, pp. 443–446.

[18] Dixey, F., "Bauxite Deposits in Nyasaland," *Mining Mag.* (London), Vol. 33, pp. 201–205, 1925, and "Geology and Mineral Resources of Nyasaland," *Ibid.*, Vol. 24, pp. 201–212, 1926.

[19] Emory, L. T., "British Guiana Beauxite Deposits," *Min. and Met.*, Vol. 9, pp. 8-11, 1928.

present time are in the form of lenses in the sand-clay belt of the coastal plain. In Dutch Guiana the deposits are very like those of British Guiana.[20]

PRODUCTION

UNITED STATES.—During 1927 the total quantity of bauxite produced in the United States was 320,940 long tons, valued at $1,988,780. Of this amount 62,410 tons were sold for use in the chemical industries and 71,790 tons for abrasives and in refractories. Nearly all the remainder was made into aluminium. The value of aluminium salts made from bauxite was $14,288,430.

Most of the bauxite mined in the United States comes from Arkansas. About 13,050 tons were produced in Georgia and 4,060 tons in Alabama. Workable deposits of bauxite are known to occur also in Tennessee,[21] California and Mississippi.[22]

The imports of bauxite in 1927 were 356,580 long tons valued at $1,572,236. Of this about 332,000 tons came from British and Dutch Guiana, and most of the balance from France. Imports of aluminium salts were 1,845 tons, valued at $83,288.

TABLE LXIV.—WORLD'S PRODUCTION OF BAUXITE IN 1927
(In Metric Tons)

Countries	*Tons*	*Countries*	*Tons*
France	540,000	Yugoslavia	100,327
United States	326,091	Italy	95,300
Dutch Guiana	180,691	Other Countries	20,000±
British Guiana	163,454		

[20] Kilinski, E. A., "Notes on Dutch Guiana," *Min. and Met.*, Vol. 9, pp. 59–61, 1928.

[21] Ashley, G. H., "Bauxite Mining in Tennessee," Resources of Tenn., Vol. 1, pp. 211, 219, 1911.

[22] Burchard, E. F., "Bauxite in Northeastern Mississippi," U. S. Geol. Sur., *Bull.* 750–G., 1925.

The exports were 121,858 tons of bauxite and bauxite concentrates valued at $7,800,491 and 21,128 tons of aluminium sulphate valued at $491,317.

World.—The world's production was about 1,330,000 metric tons divided as in table on p. 379.

OTHER ALUMINOUS COMPOUNDS

Among the aluminous compounds that have recently come into use as a source of alumina in the ceramic industry are diaspore, sillimanite, kyanite, dumortierite and andalusite. Formerly these were not known in large enough deposits to afford a sufficient supply for commercial purposes. Recently, however, search has discovered large quantities of andalusite in California and there is promise of the discovery soon of deposits of sillimanite and kyanite that may be of commercial importance. Not only is there a demand from the potters for aluminous materials, but it has been learned that aluminous refractories are much more satisfactory than firebrick for certain purposes. Bauxite has, heretofore, been used for these, but diaspore is replacing it in some factories.

Diaspore.—Diaspore (AlO.OH) is used almost exclusively for firebrick, though a small quantity is used in the manufacture of abrasives. The only commercial occurrence of the mineral is in the North Central Ozark region of Missouri,[23] where a diaspore clay containing 70% and more of alumina is mined. The deposits are in pockets of flint clay in sandstone. The proportion of diaspore increases toward the centers of the deposits, and at the centers are the high-grade materials. An analysis of a sample of good "clay" gave:

Moist	Ign.	SiO_2	Al_2O_3	Fe_2O_3	Na_2O	K_2O	Total
.60	14.00	9.30	73.73	.57	2.00	.52	100.72

[23] Mysore, D. C., "Diaspore Clay of Arkansas and Missouri," Amer. Cer. Soc., *Jour.*, Vol. 6, pp. 501–9, 1923.

In 1927 the output of Missouri was 40,085 short tons, valued at $229,093. All was used in the manufacture of refractory brick.

ANDALUSITE.—Andalusite (Al_2SiO_5), after diaspore, with about 62% of Al_2O_3, is at present the most important of the substances mentioned above. Most of it comes from the Inyo Mountains, California, though small quantities have been shipped from South Dakota for experimental use. The production in California is at the rate of about 3,600 tons per year.

It occurs as a constituent of crystalline schists and other crystalline rocks of contact and dynamic metamorphic origin usually disseminated among their other components from which it cannot be separated commercially. In the White Mountains of the Inyo Range, Mono County, California, it is found in large crystals and radial masses mixed with corundum, lazulite, pyrophyllite, muscovite, rutile, pyrite and a few other minerals in a large deposit thought to contain several millions of tons.[24] The mass apparently consists of 75% to 85% andalusite, but its analyses show over 90% Al_2SiO_5, the excess being due probably to the presence of corundum.

An analysis of the andalusite rock from White Mountain, California, gave:

SiO_2	Al_2O_3	H_2O	Ign.	Other Const.		TOTAL
33.78	56.89	.37	3.67	5.37	=	100.08

Andalusite is being used in the manufacture of spark-plug porcelain, but if it can be produced cheaply it may be used as a source of alumina in many other ceramic processes. Its value depends upon the fact that it inverts at about 1390° C. to mullite [25] and glass.

[24] Melhase, J., "Andalusite in California." *Eng. and Min. Jour.-Press*, Vol. 120, pp. 91–94, 1925.

[25] Peck, A. B., "Note on Andalusite from California: A New Use and Some Thermal Properties," *Amer. Mineralogist*, Vol. 9, pp. 123–129, 1924.

KYANITE.—Kyanite (Al_2SiO_5) contains the same chemical elements as andalusite and in the same proportions. Like andalusite it also inverts to mullite and glass, and therefore should serve the same purposes as this mineral. Unfortunately, however, in the inversion of kyanite an expansion ensues which results in the production of a friable mass, the injurious effects of which may, however, be overcome by calcining the kyanite before introducing it into the procelain mixture. Transparent varieties are sometimes cut for gems.

In most places kyanite occurs in comparatively small bladed crystals, in fibrous masses and in radial aggregates in metamorphic rocks, from the other constituents of which it cannot be separated easily. Large deposits which may be of commercial importance are reported to exist near Wheatland, Wyoming, near Charlotte Courthouse, Virginia, and in northern Manitoba. It occurs also in large amounts in Cherokee and neighboring counties in northwestern Georgia. Whether these occurrences will furnish sufficient material of satisfactory quality to meet the demands of the manufacturers is not yet known.

In Georgia, kyanite is an important constituent of crystalline schists that are metamorphosed Cambrian sediments and on the sides of quartz veins cutting them. Some of the groups of crystals are very large, weighing several hundred pounds. Many bowlders composed of mixtures of kyanite and quartz are scattered over the northern part of the State close to the North Carolina line.

In Manitoba [26] the kyanite is one of the components of a pre-Cambrian chlorite schist which contains also staurolite and garnet. Through this is a 6-foot thick layer of

[26] Wallace, R. C., "An Unusual Occurrence of Cyanite," *Amer. Mineralogist*, Vol. 9, pp. 129–135, 1924.

mica schist in which are white and reddish kyanite crystals in radiate groups, alternating with layers in which staurolite is the predominant mineral and others of a garnet-mica schist. The series is believed to be sedimentary, and the kyanite to be the result of contact action in the neighborhood of granite.

SILLIMANITE.—Sillimanite (Al_2SiO_5) like andalusite and kyanite may be used as a source of alumina in ceramic products, but the temperature to which it must be raised to convert it into mullite and glass is much higher than that used to convert the other two minerals.[27]

Sillimanite is known to occur as a common constituent of metamorphosed aluminous sediments at a great many places in the United States and Europe, but usually is so intimately intermingled with the other components of the schists that the cost of separating it on a commercial scale is very great. Recently a large deposit of exceptionally pure material has been found in Assam, India, but little is known of its size. Another is known near Custer, South Dakota, where it has been mined to a slight extent for experimental use.

DUMORTIERITE.—Dumortierite ($Al(AlO)_7H(BO)(SiO_4)_3$) is a borosilicate containing about 64% of Al_2O_3. It occurs as a constituent of many gneisses and pegmatites, often associated with kyanite, andalusite and sillimanite. It is probably a product of the action of magmatic gases on aluminous silicates. Rarely does it occur in deposits large enough to be of commercial importance, but recently it has been found in a comparatively large quantity in sericite schists at Lincoln Hill and Limerick Canyon in the Rochester mining district in Nevada.[28]

[27] Peck, A. B., "Changes in the Constitution and Microstructure of Andalusite, Cyanite and Sillimanite at High Temperatures and Their Significance in Industrial Practice," *Amer. Mineralogist*, Vol. 10, pp. 253-280, 1925.

[28] Fairbanks, E. E., "Dumortierite from Nevada," *Amer. Mineralogist*, Vol. 11, pp. 93–96, 1926.

The dumortierite at Limerick Canyon occurs in a vein-like schistose mass 14 feet wide cutting a mixture of quartz and andalusite. This mass consists of an intimate intergrowth of muscovite and minute prismatic crystals of dumortierite, a little andalusite and quartz and tiny grains of rutile. Its analysis gave:

SiO_2	Al_2O_3	TiO_2	B_2O_3	Others		Dumortierite	Muscovite	SiO_2	Others
37.05	55.01	.63	4.65	2.66	=	75.33	14.16	8.53	1.98

Dumortierite [29] dissociates into mullite and glass at about 1250° C. and becomes white. The mineral, however, does not fuse until the temperature rises to 1810° C., consequently, even in its crude state, it may become a valuable ingredient in mixtures used for making refractory products and high-grade porcelain. It is now being used experimentally in special porcelains.

ALUMINIUM SALTS

The total production of aluminous salts in the United States during 1927 was 378,770 short tons, valued at $14,288,430. In their manufacture were used 137,870 long tons of bauxite, 720 tons of aluminium, 2,780 tons of aluminium hydroxide,[30] and an unrecorded amount of high-alumina clay. The principal salts made were 19,430 tons of alums and 336,420 tons of the sulphate. The imports of all kinds of aluminous salts were 1,845 tons, valued at $84,288, and the exports 21,128 tons, valued at $491,317.

ZIRCONIA

The principal sources of zirconium and zirconium oxide, or zirconia, are zircon ($ZrSiO_4$) and baddeleyite. In the

[29] Peck, A. B., "Dumortierite as a Commercial Mineral," *Amer. Mineralogist*, Vol. 11, pp. 96–101, 1926.

[30] Curtis. F. J., "Marketing Alums and Aluminium Salts," *Chem. Met. Eng.*, Vol. 33, pp. 687–89, 1926.

trade usage the name baddeleyite is limited to crystals of zirconium oxide (ZrO_2), fibrous forms being known as brazilite. The ore zirkite [31] is a mixture of one of these and zircon and a supposed new silicate of zirconium that has not yet been named.

The metal zirconium is used as a steel hardener in the manufacture of armor plate, and of certain high speed alloys such as "cooperite," which requires no tempering. For these purposes the metal should be free from hafnium.

The principal use of zirconia is in the manufacture of porcelain and refractory materials, such as combustion tubes, crucibles, electric furnace lining, etc. Because of its very low linear coefficient of expansion (0.00000084) the pure fused oxide can be subjected to sudden changes of temperature without breaking. It must, however, be practically free from iron, titanium and silica. Recently it has come into use as a substitute for tin oxide in enameling metal ware. Transparent varieties of zircon are used as gems (see p. 330).

Zircon occurs in many rocks but it is found at only a few places in sufficient quantity to be of commercial importance.

Only a small quantity of zircon has been produced in the United States. Some of this has come from a pegmatite dike near Tuxeda in Henderson County, North Carolina [32] where a little less than 40 tons have been produced. A very small amount has been saved also from the monazite washings (see pp. 387–388) in the Carolinas. Most of the zircon now being obtained comes from a stretch of beach 4 miles south of Pablo Beach in Florida, where about 16% of the sand consists of ilmenite, zircon,

[31] Thompson, J. G., "A Preliminary Study of Zirkite Ore," *Jour. of Phys. Chem.*, Vol. 26, pp. 812–832, 1922.

[32] Schaller, W. T., "Thorium, Zirconium and Rare Earth Minerals," U. S. Geol. Sur., *Min. Res., 1919*, Pt. II, p. 19, 1922.

epidote, rutile, staurolite and other heavy minerals. From this place 624 tons of zircon were shipped in 1925. Zircon occurs also in commercial quantities in a thin bed of zircon-bearing sandstone, near Ashland,[33] Virginia, and in pegmatites and magnetite ores in Sussex and other northern counties in New Jersey and in a pegmatite in north central Wisconsin.

The most important sources of the mineral are in the States of Bahia, Espirito Santo and Rio de Janeiro, Brazil and near Travancore, India. At these places it occurs with monazite and ilmenite in deposits of sand. (See p. 389.) In 1924 the exports from Brazil were 764 metric tons, but work ceased before the end of the year, because of inability to meet expenses.

Zirkite and baddeleyite are known only in Brazil about 130 miles north of the city of São Paulo. Baddeleyite occurs as loose pebbles in stream beds and zirkite as gravel and pebbles embedded in a red clay and as a compact vein of the almost pure material. The quantity in the vein is said to be very great.

TABLE LXV.—ANALYSES OF ZIRKITE FROM BRAZIL

	ZrO_2	SiO_2	TiO_2	Fe_2O_3	H_2O	TOTAL
Glassy variety	94.12	2.41	.98	3.22	...	100.73
Pebbles	74.48	14.08	1.35	10.26	...	100.17
Commercial ore	68.93	20.30	.60	3.59	.80	100.22

The quantity and value of the zirconium minerals produced during the past few years is not known, but in 1913 the Brazilian production was 1,119 short tons of zirkite valued at $54,767. In the last half of the year 1918 the imports into the United States were 1,608 tons valued at $77,250. In 1926 no zirconium ore was imported but there were imports of 783 lbs. of iron-zirconium alloys.

[33] Watson, T. L. and Hess, F. L., "Zirconiferous Sandstone, Near Ashland, Virginia," U. S. Geol. Sur., *Bull.* 530, pp. 165–171, 1913.

CHAPTER XIV

MONAZITE AND THORIUM MINERALS

MONAZITE

Monazite is a component of pegmatites and granites. It occurs in very small quantity scattered indiscriminately through the rocks, but is concentrated in the sands of streams from which it is separated by washing.

The mineral is essentially (Ce.Di.La) PO_4, but it nearly always contains some $ThSiO_4$, varying from a trace to 20% ThO_2; consequently it is regarded as a solid solution of these substances. Its value depends mainly upon the presence of thorium, of which monazite is the principal source. The metal is the characteristic constituent of the salts used in making incandescent gas mantles.[1] Since, however, electrical illumination has practically destroyed the demand for gas mantles, the market for thorium has likewise been largely destroyed.

Formerly monazite was produced in large quantity in the Carolinas (Fig. 115), the production in 1909 amounting to 542,000 lbs. valued at $65,000, and in 1905 to 1,350,418 lbs. valued at $163,908. All of this was made into $Th(NO_3)_4$, but the demand exceeding the supply large quantities of the nitrate were imported.

Later large deposits of the sand were discovered in Brazil. Because the Brazilian monazite contains more thorium than the domestic mineral, nearly all mining ceased in the Carolinas in 1910–11. The average ThO_2

[1] Kithil, K. L., "Monazite, Thorium, and Mesothorium," U. S. Bur. Mines. *Tech. Paper*, 110, 1915.

content of the American monazite is about 4%–5%, and that of the Brazilian mineral is about 6%. Still later immense deposits of monazite sand were discovered in India, and this in turn drove Brazilian sand from the market because its content of ThO_2 is about 9%.

The deposits in the Carolinas cover an area of about 3,500 square miles, lying in an oval in the Piedmont

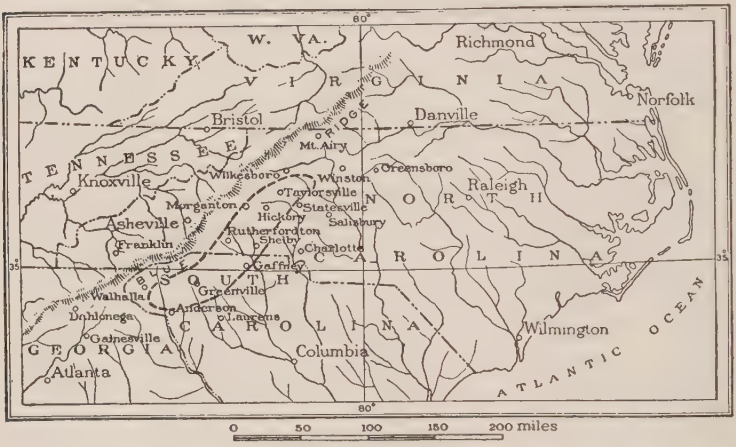


Fig. 115.—Map showing area of monazite deposits of known commercial value in the Southern appalachian region. (*After Sterrett, U. S. Geol. Sur., Bull. 340.*)

Plateau at the base of the Blue Ridge Mountains.[2] The sands contain nearly all the heavy minerals left by the disintegration of the crystalline rocks. These were separated by washing or by magnetic processes and the resulting residual was largely monazite.

Monazite sand is also known to occur near Weippe, Nez Perce County, Idaho,[3] but not in sufficient quantity

[2] Sterrett, D. B., "Monazite Deposits of the Carolinas," U. S. Geol. Sur., *Bull.* 340, pp. 272–285, 1908, and

Pratt, J. H., "Zircon, Monazite and Other Minerals Used in the Production of Chemical Compounds Employed in the Manufacture of Lighting Apparatus," N. C. Geol. Sur., *Bull.* 25, 1916.

[3] Schrader, F. C., "An Occurrence of Monazite in Northern Idaho," U. S. Geol. Sur., *Bull.* 430, pp. 184–191, 1910.

to be of commercial importance at present. The sand contains 40% of monazite, in which, however, there is only 3% of ThO_2.

The Brazilian deposits [4] lie along the coast near Rio de Janeiro and in the sandy beds of rivers entering the ocean along this coast. At first the sand was shipped as found, since it had been sufficiently concentrated by the waves to be of commercial quality. Later it was concentrated to contain 85% of the monazite, all of which was exported.

In India, monazite sand is widely distributed over the State of Travancore, but is concentrated particularly on the sea coasts, where in some places the mineral constitutes about 50% of the total sand, the principal other components being ilmenite and zircon. Its original source is pegmatites.

The reserves in the Travancore field [5] aggregate at least 2,000,000 tons of monazite on the assumption of a 10% content and a thickness of only 2 feet of sand.

Monazite is known to occur in commercial quantities in Ceylon, in the Malay Peninsula, [6] in Western Australia [7] and at a few other places, nearly always in pegmatites that contain tin ore. [8]

The World's production of monazite in 1909, 1914, 1918 and 1924 is given in table on p. 390.

In 1925 there was a little production in the United States and Ceylon but none has been reported from either India or Brazil.

[4] Gottschalk, A. L. M., "Brazilian Monazite Sands Lie in Coastal Strip," *Min. and Eng. World*, Vol. 42, p. 903, 1915.

Schaller, W. T., "Thorium, Zirconium and Rare-earth Minerals," U. S. Geol. Sur., *Min. Res., 1918*, Pt. II, pp. 1–32, 1922.

[5] "Monazite in Southern India," *Min. Jour.*, London, Aug. 10, 1912.

[6] "Occurrence of Monazite in the Tin-bearing Alluvium of the Malay Peninsula," Imp. Inst., *Bull.* Vol. 4, pp. 301–308, 1906.

[7] Simpson, E. S., "The Occurrence of Monazite at Cooglegong and Moolyella," West Australia Geol. Sur., *Bull.* 48, 1913.

[8] "Recent Work on Monazite and Other Thorium Minerals in Ceylon," Imp. Inst., *Bull.* Vol. 14, pp. 321–369, 1916.

TABLE LXVI.—WORLD'S PRODUCTION OF MONAZITE
(In Short Tons)

	United States	*Brazil*	*India*	*Ceylon*
1909.....	271	7,121	.....	.....
1914.....	...	661	1,328	.....
1918.....	...	551	2,371	.....
1924.....	small	...	633	small

The imports of thorium compounds into the United States during 1926 were about 670,000 lbs. of monazite sand, valued at $23,800, about 21,400 lbs. of thorium nitrate valued at $27,900 and 13 lbs. of thorium oxide valued at $20.00.

OTHER THORIUM MINERALS

Other minerals that may become sources of thorium oxide are:

Thorite ($ThSiO_4$) in Norway and Ceylon, containing 49–74% ThO_2,

Auerlite (thorium silico-phosphate) in Henderson County, North Carolina, containing 70% ThO_2,

Thorianite (ThO_2) in Ceylon, containing 59% to 93% ThO_2, and several others of slight importance.

Thorianite is known also to occur in the United States, Madagascar and Russia but only in small quantity. Small shipments of thorite have been made from Norway and Ceylon and a few pounds of auerlite have been produced at Zirconia, North Carolina. Thorianite was formerly separated from the tailings of gem washing near Belangoda, Ceylon, at the rate of 20,000 lbs. per year, but recently all shipments have ceased.

As thorianite is exceedingly rich in thorium it brings a corresponding high price. In 1911 when 8,818 lbs. were produced it was quoted at $7.00 per lb., while monazite was quoted at an average of 8 cents.

CHAPTER XV

LITHIUM MINERALS

Spodumene ($LiAl(SiO_3)_2$), lepidolite ($((Li.K.Na)_2((Al.Fe)OH)_2(SiO_3)_3$), and amblygonite ($Li(Al(F.OH))PO_4$) are the principal sources of lithium compounds. The former is also used as a gem, under the names hiddenite and kunzite.

Lithium salts are used in medicinal compounds, in photography, in the manufacture of fireworks and glass and in storage batteries.

Lepidolite is a rose-colored mica containing about 4% of LiO_2. It often accompanies tin-stone and tourmaline in pegmatites or in veins filled by pneumatolitic processes. It occurs in all tin-producing regions where the tin-stone is associated with pegmatite, as at Jekaterinburg in Russia, at Mt. Hradisko in Moravia, at Schnittenhofen in Bohemia, at Penig in Saxony, at Uto in Sweden, in western Australia, at Wakefield, Canada, in the southern Black Hills, South Dakota, and in gem tourmaline localities in Maine and California.

Spodumene is a lithium pyroxene containing 7½% of LiO_2. It occurs in pegmatites, granites and often in crystalline schists where they have been acted upon by magmatic gases. The most notable localities of the mineral in this country are Huntington, Massachusetts, Branchville, Connecticut, and the Etta Mine in the Black Hills. In all these places it is associated with other pneumatolitic minerals and often with cassiterite and lepidolite. Its crystals are often enormous in size, some of them in the mines of South Dakota measuring 42 feet

long and 3 to 6 feet in cross-section (Fig. 116). From one crystal 37 tons of marketable spodumene were taken. In spite of this large size it is estimated that 25 tons of material must be removed to extract one ton of spodumene.[1]

A glassy, emerald-green, transparent spodumene from a druse in pegmatite, near Stony Point, Alexander County, North Carolina,[2] is known as hiddenite and a pink or

Fig. 116.—View at Etta Spodumene mine, Black Hills, S. D., showing large crystal of spodumene. (*Courtesy of Pres. C. C. O'Harra, S. D. State School of Mines.*)

lilac variety from Diego County, California,[3] is known as kunzite. Both are used as gems.

At one time kunzite was fashionable and was produced to the value of $18,000 annually. This rapidly fell to about $600 annually and at present only small quantities enter the market.

[1] Schaller, W. T., "Mineralogical Notes, Series 3," U. S. Geol. Sur., *Bull.* 610, p. 138, 1916, and *Bull.* 666, p. 157, 1919.

Schwartz, G. M., "The Black Hills Mineral Region," *Amer. Mineralogist*, Vol. 13, pp. 56–63, 1928.

[2] Kunz, G. F., "History of the Gems Found in North Carolina," N. C. Geol. Sur., *Bull.* 12, 1907.

[3] Kunz, G. F., "Gems, Jewelers' Materials and Ornamental Stones of California," Calif. State Min. Bur., *Bull.* 37, 1905.

Hiddenite has never been used in large quantity.

Amblygonite has long been employed in France as a source of lithium, but it is only recently that it has been produced in the Harney Peak district, South Dakota, for this purpose. The mineral contains about 9.8% of Li_2O_2 and is therefore the most valuable source of lithia. It, however, is not widely spread though it occurs in large quantity at a few places.[4]

It is found in the Peerless Mine, near the Etta Mine in the Black Hills, as large nodular masses, some of which weigh ½ ton, and many 400 lbs. or more. They are always in pegmatite.

In California amblygonite occurs in dikes containing lepidolite, usually forming distinct lenses some of which measure 25 x 12 x 14 feet. Amblygonite is also encountered in the tourmaline mines of Maine and at Dixon, New Mexico.

The United States produces about 10,000 tons of all the lithium minerals annually, having a value of about $160,000, California and South Dakota furnishing the greater part. Spain produces annually about 20 tons and France and Australia a few tons in some years.

Normally a few hundred tons are exported. Formerly much of the material that was exported as crude ore was imported later as special compounds, but since the war, the United States has made its own lithium salts and is in a position to export some of them, since the domestic supply of crude ore is larger than that of any other country.

It is probable that lithia minerals are produced also in other countries from which there are no statistics. France is known to have mined amblygonite and the output of Germany in lithia salts is larger than its recorded importation of crude material would supply.

[4] Schaller, W. T., "Lithium Minerals," U. S. Geol. Sur., *Min. Res., 1916*, Pt. I, pp. 8–17, 1917.

In Sweden petalite ($LiAl(Si_2O_5)_2$) occurs in a pegmatite dike from which gem tourmaline is mined and this is its only known commercial source. It has been mined on a small scale and it is reported that an abundance of the material remains in the mine at Uto.

In France the same mineral occurs in a pegmatite at Montebras, in northwest Spain at the San Finx tin mine, and in Western Australia it occurs with lepidolite and spodumene in sufficient quantity to supply the world.

At none of these occurrences, however, is it now being worked.

Zinnwaldite, a mica, containing about 10% of FeO and from 3% to 5% LiO_2, has been mined in Bohemia and Saxony.

CHAPTER XVI

CALCITE AND LIMESTONE

Limestone is formed mainly by the secretion of animals or plants, but a smaller portion is produced by the evaporation of water (especially of hot springs) containing calcium bicarbonate, which it has taken up during its travels through the crust by virtue of its content of CO_2.

CALCITE

Calcite deposited from solution may precipitate as a form of travertine, or calcareous sinter, which differs from travertine formed by organisms mainly in its mode of origin. It is of no commercial value.

Where water depositing calcite or magnesium carbonates drips from the roofs of caves it forms stalactites.[1] Compact masses may be cut and polished to show their concentric growth. In this form the material is known as Mexican onyx [2] and is utilized as an ornamental stone. While onyx marble is known to occur in Arizona, South Dakota, California and Colorado it is not exploited. Most of the Mexican onyx used in this country comes from Mexico, Algeria and Egypt. Its price varies according to beauty from 50 cents to $50 per cubic foot. About $40,000 worth is imported annually.

Vein calcite if transparent and in large untwinned

[1] Merrill, G. P., "On the Formation of Stalactites and Gypsum Incrustations in Caves," U. S. Nat. Mus., *Proc.*, Vol. 17, pp. 77–81, 1894.

[2] Merrill, G. P., "The Onyx Marbles; Their Origin, Composition and Uses, Both Ancient and Modern," Smithsonian Inst., *Ann. Rep.*, 1893. U. S. Nat. Mus., *Rep.*, pp. 539–585, 1895.

crystals with a smooth cleavage is used in making prisms for polarizing light. The value of the mineral for this purpose depends upon its perfect transparency and its high double refraction.

The best calcite [3] occurs at Helgustadir, Iceland, hence the name "Iceland Spar." Crystals are found imbedded in clay pockets in basaltic lavas. In the United States material suitable for optical instruments occurs in veins at Cedarville, California, and Greycliff, Montana. It has been reported to occur also in Nevada and at places in Spain and Argentina, and near Trout Lake, British Columbia.

LIMESTONE

Limestone is mainly the accumulation of sand, mud and the more or less broken or pulverized calcareous shells and skeletons of animals and plants that have been cemented by the solution of some portions of the calcareous material and the precipitation of the dissolved substance between the remains of the fragments. Where the shells consist partly of aragonite this dissolves and calcite is precipitated. Pressure compacts the materials, causes solution where the stresses are greatest and precipitation where they are more feeble. By repeated solution and deposition the fragmental character of the accumulation is destroyed and a compact crystalline rock results.

Most limestones contain more or less $MgCO_3$. If the proportion of this is comparatively small the rock is known as magnesian limestone, or if the proportion of the $MgCO_3$ and $CaCO_3$ present approach the ratio 1:1 it is known as dolomite. Magnesian and dolomitic limestones are used in the manufacture of magnesium compounds, and for making certain kinds of lime. (See pp. 418–419.)

[3] Bowles, Oliver, "Iceland Spar," U. S. Bur. of Mines, *Reports of Investigations*, Serial No. 2338, April, 1920.

Limestones of all kinds are used as fertilizers, as fluxes, as the sources of calcium in the manufacture of chemicals and in making lime and Portland cements. Compact varieties are employed as building stones, and, when crushed, for railroad ballast, for riprapping and as a filler in concrete. Special forms of limestone are used for special purposes.

Limestones occur in beds of all ages, but those of more recent ages are usually less compact than the older ones and consequently are not as suitable for some uses as the latter.

LITHOGRAPHIC STONE.—Lithographic stone is an exceedingly fine-grained limestone, whether pure calcite or dolomitic, the physical character of which can meet certain very precise demands. It must be uniformly fine-grained, compact, of sufficient porosity to absorb grease enough to hold just the proper quantity of ink, and must be soft enough to yield easily to the engraver's tool.

The best lithographic stone comes from Solenhofen in Bavaria where it occurs as a bed in Jurassic limestones. The quarry has been worked for a number of years and the best material has been removed. A large deposit of excellent stone containing millions of tons of workable material is reported to exist near Dairen, Manchuria, but it has not yet been developed.[4] A fairly satisfactory stone occurs also at Brandenburg,[5] Kentucky, as a bed 3 feet thick, and in Iowa.[6] The Kentucky locality furnishes some stones, but the demand for lithographic stone

[4] Nishihara, H., "Lithographic Stone," Queensland Govt., *Min. Jour.*, Vol. 27, p. 358, 1926.

[5] Ulrich, E. O., "The Lithographic Stone Deposits of Eastern Kentucky," *Eng. and Min. Jour.-Press*, Vol. 73, pp. 895–896, 1902.

[6] Hoen, A., "Discussion of the Requisite Qualities of Lithographic Limestone, with Report on Tests of the Lithographic Stone of Mitchell County, Iowa," Ia. Geol. Sur., Vol. 13, pp. 339–352, 1903.

is slight and is becoming less, as zinc and aluminium plates are replacing it in most lithographic operations.

Chalk.—Chalk is a fine, earthy material composed mainly of the tests of foraminifera (Fig. 117), mixed to a slight extent with the spicules of sponges, flint, etc. It occurs as thick beds of Cretaceous and later ages. Whiting

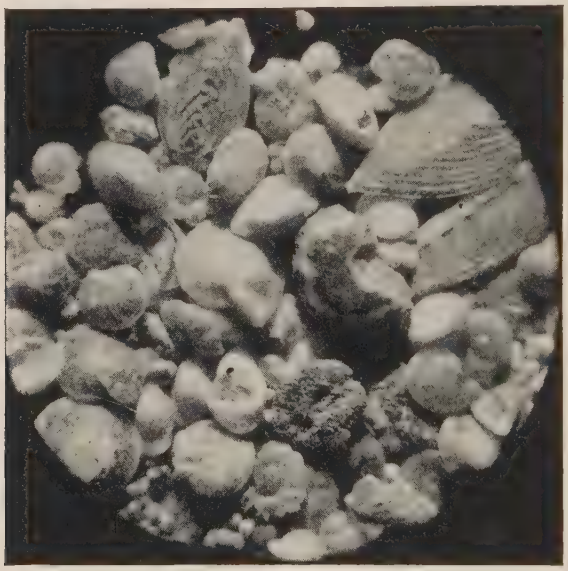


Fig. 117.—Microphotograph of foraminifera from well-cuttings. (*Courtesy of W. E. Pratt, Humble Oil & Refining Co., Houston, Texas.*)

is a pulverized chalk. Chalk and whiting are used chiefly as pigments, as fillers in linoleum, rubber and putty, as abrasives and polishers, in the manufacture of crayons, in the production of carbonic acid gas, as a flux, as a glaze for ceramic products and paper, and in the manufacture of Portland cement.

Most of the chalk occurring in the United States contains too many impurities to be regarded as of high grade. Most of that quarried in South Dakota, Nebraska, Kan-

sas, Arkansas, Mississippi and Texas is employed in the manufacture of Portland cement.

The best chalk comes from England, France, Belgium and Denmark. Before the war about 170,000 long tons of chalk, valued at $120,000, were imported annually into the United States, and about 1,750 tons of whiting valued at $14,000. Most of the crude chalk is ground into whiting.

MARL.—Marl is a porous mass composed largely of calcium and magnesium carbonates that accumulate in the bottoms of fresh water lakes and in swamps, as the result of chemical precipitation and the fall of the tests of tiny animals, mixed with some clay and more or less sand. According to some students of marl much of the carbonate precipitated is due to the action of aquatic plants in absorbing the carbon dioxide from the water in which they live and so rendering insoluble any calcium carbonate that may be present in it. In many places shells composed of calcium phosphate and bones of aquatic animals are also present in the marl.[7]

Marls that are nearly pure calcium carbonate are used to some extent in making cement. Impure marls, and especially those containing phosphate, are used as fertilizers.

PRODUCTION

The production of limestone in the United States during 1927 for other uses than the manufacture of lime and cements was 99,662,270 short tons valued at $112,439,824. Of this, the value of the rock used for building was $18,820,045, that used for flux was $15,977,484, that crushed for use as railroad ballast, road metal and in concrete was $63,411,465, that used in

[7] Davis, C. A., "A Contribution to the Natural History of Marl," *Jour. of Geol.*, Vol. 8, pp. 485–497, 1900, and Vol. 9, pp. 491 506, 1901.
Hale, D. J., "Marl (Bog Lime)," Mich. Geol. Sur., Vol. 8, Pt. 3, 1903.

chemical works $5,703,701, and that employed in agriculture was $3,360,704. Indiana, New York, Ohio and Pennsylvania were the largest producers. In addition there were used in the manufacture of Portland cement 43,800,000 short tons, in the making of natural cement 395,000 tons and in the making of lime 8,830,000 tons. The total production of limestone for all purposes was 152,687,270 tons.

MARBLE

When limestones and dolomites are subjected to metamorphism, and are recrystallized so that the siliceous impurities become silicates and the carbonates form interlocking crystal particles, they are known as marbles. Marbles are used as building and ornamental stones, and for all purposes for which limestones are employed.

The production of marble for building purposes in 1927 was 2,823,790 cubic feet valued at $10,739,228, for monumental stone 1,127,480 cubic feet valued at $4,097,249, and for stucco, terrazzo and other purposes 266,240 short tons valued at $789,395, or a total of 600,060 tons valued at $15,625,872. Of this amount the principal producers were:

Vermont	168,070 tons	valued at $5,096,716
Tennessee	181,870 tons	valued at $4,170,345
Georgia	54,520 tons	valued at $3,065,579
Missouri	67,460 tons	valued at $1,108,159

The exports were valued at $237,233 and imports at $3,404,486.

CHAPTER XVII

LIME

GENERAL

When limestones are heated, the carbon dioxide and the water they contain are driven off at 898° C., leaving a porous mass of CaO, quick lime, which when mixed with water slakes and forms $Ca(OH)_2$. In the process swelling occurs and heat is evolved. The slaking is retarded by the presence of magnesia and by argillaceous impurities, consequently the purest calcareous limestones are sought by the lime-makers, if their product is to be used in mortar or in quick-setting plasters.

The "fat" limes contain but little impurity. They slake rapidly, and when exposed to the air absorb CO_2 and change back to calcite. The "meager" limes, containing magnesia, slake a little more slowly than the fat limes, but for some purposes are preferable to the latter. When the sum of the silica, Fe_2O_3 and Al_2O_3 exceeds 5% the product of calcination does not slake and is not known technically as lime.

The National Lime Manufacturers Association classifies lime as:

High-calcium lime with less than 5% MgO
Magnesian lime with between 5% and 25% MgO
Dolomitic lime with between 25% and 45% MgO
Superdolomitic lime with more than 45% MgO

Within recent years lime that has been hydrated has been placed on the market in the expectation that it would air-slake (combine with CO_2) less rapidly than

lump lime and therefore would keep for a long time. This has been found not to be the case, but since the hydrated lime is prepared as a very fine powder it is convenient to handle, and because of its fineness, it often coats itself with a layer of carbonate which prevents access of air to the interior of the mass and effectually protects it against slaking.

The advantages of hydrated lime over lump lime are: the greater ease with which it is handled, its better keeping qualities and the fact that it does not require slaking, saving time and labor and the waste due to unskilled slaking. Moreover, it contains no unburned rock or overburned lime (a sinter made by union of the calcium with impurities), which is waste, but on the other hand it contains about 20% water on which freight must be paid.

USES

The main types of lime classified according to use are:

Building lime, for mortar, plaster or stucco
Finishing lime, either alone or with plaster-of-Paris, for white-washing and coating
Agricultural lime for use as fertilizer
Chemical lime

About 200 lbs. of lime of high quality will produce 10 cubic feet of "putty" with which sand is mixed to make mortar. Impurities, underburning and overburning decrease the volume of putty and consequently decrease the quantity of mortar that can be made from it. Moreover, the presence of MgO in the lime decreases the stickiness and thus its holding capacity for sand. Therefore a magnesian lime will not make as much mortar as a high calcium lime but it will be stronger (about 3 times as strong if a "dolomitic lime"). This strength, however, is of little importance, since for strong mortars cement is

preferable. When Portland cement is mixed with hydrated lime the resulting cement mortar is easily worked and is practically water proof. For making cement mortar a high magnesian hydrated lime is preferable to a high calcium variety, since it makes a stronger mortar. If the ratio of the lime to the Portland cement in the mixture is less than 1:3 by weight, the mortar is as strong as pure cement, and it hardens better under water.

For finishing lime magnesian varieties are preferred because they work better under the trowel. The "pitting" often seen on "finished walls" is due to improper slaking. The lime particles are unhydrated when placed on the wall and later are hydrated. Hence hydrated lime is preferable to lump lime for finishing plasters.

For agricultural use magnesian lime is thought to be of greater value than lime free from magnesia.

The principal uses of chemical lime are: in making sand-lime brick, in making glass, as a flux in metallurgical processes, in water softening, in the manufacture of soda-ash, bleaching powders, calcium carbide, in purifying illuminating gas, in making calcium cyanamide and calcium nitrate (both of which are fertilizers), sprays, in clarifying sugar, in the preparation of wood distillates, in the manufacture of paper, cold-water paint and glycerine, etc., for "depilation" of hides before tanning and for the preparation of many chemical compounds.

For most of these purposes the high calcium limes are the best.[1]

PRODUCTION

The total amount of lime sold by producers in the United States during 1927 was 4,414,932 short tons valued

[1] Burchard, E. F., "The Source, Manufacture and Use of Lime," U. S. Geol. Sur., *Min. Res., 1913*, Pt. II, pp. 1509–1593, 1914.
Eckel, E. C., *Cements, Limes and Plasters*, 2nd Ed., pp. xii and 655, New York, 1922.

at $38,638,413, of which 1,596,906 tons with a value of $14,581,695 was hydrated. The amounts used for various purposes were as follows:

TABLE LXVII.—QUANTITY OF LIME USED IN VARIOUS INDUSTRIES IN 1927

Use	*Tons*	*Value*
Agricultural	322,893	$ 2,237,871
Building	2,148,840	20,962,759
Chemical	1,943,199	15,437,783

The value of the chemical lime used by glass works was $665,026, by metallurgical plants $2,640,658, by paper mills $3,413,030, by refractory manufacturers, $3,459,813, by water purification plants, $1,039,351, by tanneries, $501,442, and by sugar refineries $235,555.

A large additional amount of lime was burned by manufacturers for their own use. This is not included in the statistics for lime, but the stone from which it was made is included in the statistics of limestone and dolomite (pp. 399 and 419).

EXPORTS AND IMPORTS

The exports of lime in 1927 were 15,478 tons valued at $210,977, mainly to Canada, Mexico, and the West Indies, and the imports were 19,567 tons valued at $356,836, mainly from Canada.

CHAPTER XVII[1]

HYDRAULIC CEMENTS

When limestone containing certain aluminous silicates is heated above the temperature at which dissociation takes place, it sinters, i.e., the calcium in the limestone combines with the constituents of the silicates present and forms calcium silicates, aluminates and ferrites, some of which crystallize with water, producing a hard mixture known as hydraulic cement, because it can be used under water.

PRINCIPAL TYPES

The best cements are those in which the silicates, aluminates and ferrites of calcium are present in certain definite proportions and in which there is no free lime. Consequently the mixtures of limestone and aluminous materials which are to be transformed to cement must be carefully selected so that the proper proportions may be obtained. In some places a limestone is found in which appropriate proportions of calcium carbonate and aluminous silicates (clay) are present. This is crushed and burned at a temperature a little higher than that used in lime burning, making a "natural rock cement." In other places a mixture of slaked lime and a silico-aluminous slag of the proper composition, or a volcanic ash, is ground fine, yielding a "Puzzolan cement,"[1] which when mixed with water will set. In other places a siliceous limestone is heated a little above the tempera-

[1] Cox, A. G., "Volcanic Tuff as a Construction and a Cement Material," *Philippine Jour. of Sci.*, Vol. 3, pp. 391–406, 1908.

ture of decarbonation giving a "hydraulic lime." As this usually contains considerable free lime, it slakes slowly, and finally sets, but it has little strength unless mixed with large quantities of sand, and is of little importance in this country, though of great importance in Europe. The best types of hydraulic limestones contain 13%–17% SiO_2 and about 3% of Al_2O_3 and Fe_2O_3.

Special types of Portland cement have been developed to meet special demands, such as greater plasticity, waterproofing qualities, lighter color, etc. They have been given distinctive names, but are not greatly different from the ordinary type. Masonry cement is a "natural cement" designed mainly for use in mortar.

Artificial mixtures of the proper components ground fine and heated to incipient fusion and again ground fine produce the well-known Portland cement. As a more uniform mixture can be made than found, Portland cement has gradually driven from the market nearly all the Puzzolan and natural rock cements, until only small amounts of the latter are now made. The mixtures most commonly employed in making Portland cement are: bog lime, or marl, and clay; limestone and clay or shale; chalk and clay, and pure and argillaceous limestones.

Alumina cement is a comparatively new type of Portland cement made by fusing in a furnace a mixture of bauxite, coke and lime or limestone and grinding the resulting slag. It is just beginning to be used in the United States, though it has been manufactured in France since 1908.[2] It sets rapidly and possesses great strength, consequently it found much use for gun emplacements during the World War.

Natural rock and Portland cements.—The com-

[2] Eckel, E. C., "The New Alumina Cements," *Manufacturers Record*, Nov. 1, 1923, p. 87.

position of some well-known brands of rock and Portland cements follow:

TABLE LXVIII.—ANALYSES OF TWO NATURAL ROCK CEMENTS

	Ign.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	$K_2O.Na_2O$
Rosendale, N. Y. .	3.78	30.50	6.84	2.42	34.38	18.0	3.98
Cumberland, Md..	2.44	22.38	11.71	2.29	43.97	2.21	9.00

TABLE LXIX.—ANALYSES OF TWO PORTLAND CEMENTS

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
Empire.....	22.04	6.45	3.41	60.92	3.53	2.73
Alpha.....	22.62	8.76	2.66	61.46	2.92	1.53

The wide variation in the composition of the "natural rock cements" explains in part the greater favor with which the Portland cements are received by the engineering experts. The variation is due mainly to the impossibility of securing a continuous supply of limestone of uniform composition. The composition of some of the best known natural cement rocks is shown below.

TABLE LXX.—ANALYSES OF NATURAL CEMENT ROCKS

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alk	CO_2	SO_3
Utica, Ill.....	17.01	3.35	2.39	32.85	8.45	n. d.	34.12	..
Hancock, Md.....	19.81	7.35	2.41	35.76	2.18	n. d.	31.74	..
Lawrenceville, N. Y.	10.90	3.40	2.28	29.57	14.04	n. d.	37.90	.61
Lawrenceville, N. Y.	23.80	4.17	4.71	22.27	12.09	n. d.	31.00	.90
Milwaukee, Wis.....	17.56	1.46	2.24	27.14	13.89	...	26.45	..

The natural rock cements differ from Portland cement in lighter weight, quicker set, lower strength, greater latitude of composition and lower temperature of burning. Because of the less need for carefully controlled composi-

tion and because of the lower temperature allowable for burning, natural rock cements can be sold for about one-half the price of Portland cement.

In the manufacture of Portland cement a mixture of pure and argillaceous limestone is preferred to mixtures of any other kinds, because of the difficulty of preparing from other substances a mixture of uniform composition. To procure a satisfactory mixture clay must be dried and ground and shales must be very finely ground and thoroughly mixed before they can be added to the ground limestone. When argillaceous limestone is used a much smaller quantity of pure limestone is needed to raise the calcium content to the proper figure, and pure limestone is hard to find. Moreover, fine grinding and as thorough mixing is not so necessary when argillaceous limestone is used as when clay or shale and limestone are mixed, because the sinter of the impure limestone is not very different in character from the complete cement.

The composition of the components mixed to make some of the famous brands of cement are:

Table LXXI.—Analyses of Components and Mixtures of Certain Portland Cements

	SiO_2	Al_2O_3	Fe_2O_3	$CaCO_3$	$MgCO_3$	H_2O+Org.	$CaSO_4$	SO_3
Lehigh Valley, Pa.								
Shale	15.40	4.26	1.38	74.66	2.66	1.88	.86	..
Limestone	5.87	1.59		88.00	4.00	....	..	..
Mixture	13.97	5.07	1.88	74.10	2.04	1.82	..	..
Glens Falls, N. Y.				CaO	MgO			
Clay	55.27	28.15		5.84	2.25	8.37	..	.12
Limestone	3.30	1.30		52.15	1.58	....	..	.30
White Cliffs, Ark.								
Clay	53.3	23.29	9.52	.36	1.49	5.16	..	..
Chalk	7.97	1.09		88.64*a*	.73*b*	....	..	..

a. $CuCO_3$ *b*. $MgCO_3$

The usual practice is to make a mixture of 75% carbonate and 25% aluminous silicates and burn it mixed

with fine coal in rotating kilns. The "clinker" is the crude cement. This then is ground fine and sifted, or sized by air currents, and put on the market.

The clinker consists of $Ca_2(CaO)SiO_4$; Ca_2SiO_4; $Ca_3(AlO_3)_2$ and $5CaO.3Al_2O_3$. It is blue or gray and has a density of 3 to 3.25.

The raw materials must be selected with great care if a satisfactory cement is to be produced. Magnesium carbonate must not exceed 5% to 6% in the limestone used and the less the better, because it is sure to be present in the argillaceous component. The clay or shale should contain more than 55% SiO_2 and less than 70%. The ratio of $Al_2O_3 + Fe_2O_3$ to SiO_2 should be about 1:3, and alumina should not be in excess.[3] Alkalies and sulphates should not exceed 3% and no flint, chert or sand should be present. Al_2O_3 raises the vitrification point [4] and quickens the set and MgO retards the set.[5]

The setting properties of cements made from different materials and from the same materials in different proportions vary to such an extent that the Federal and many State governments now require that all cement furnished shall meet certain requirements that are specified in official instructions.[6]

Within recent years an attempt has been made to produce a cement that will not dissolve when exposed to sea water by employing iron as a base instead of calcium. Patents have been taken out for a cement in which the iron-bearing component of the mixture is glauconite, but the manufacture of iron cement has not yet been undertaken.

[3] Bleininger, A. V., "The Manufacture of Hydraulic Cements," Ohio Geol. Sur., *Bull.* 3, 1904.

[4] Bates, P. H., "Cementing Qualities of the Calcium Aluminates," U. S. Bur. of Standards, *Tech. Paper* 197, 1921.

[5] Bates, P. H., "The Properties of Portland Cement Having a High Magnesia Content," U. S. Bur. of Standards, *Tech. Paper* 102, 1918.

[6] "United States Government Specifications for Portland Cement," U. S. Bur. of Standards, *Circ.* 33, 1912, and revised Jan. 1917.

ALUMINA CEMENT.—Alumina cement,[7] however, may serve the same purpose as iron cement. It resists attacks by salt, sulphate and alkali waters that corrode ordinary Portland cement and it sets very quickly. At the end of 24 hours after pouring, its resistance to compression is 4 times as great as that of Portland cement. Its rapid hardening is due to the rapidity with which the aluminates hydrate, and its great strength to the thoroughness of the hydration and the fact that the hydrated products are largely colloidal.

The approximate composition of alumina cement is: SiO_2 = 12%; Al_2O_3 = 40%–60%; CaO = less than 40% and Fe_2O_3 = 10%.

It is reported that plants are now being constructed for the manufacture of alumina cements in the United States.

OTHER HYDRAULIC CEMENTS.—*Puzzolan-Portland cement, tufa cement, and sand cement* are made by grinding very fine a mixture of volcanic ash, sand or crushed rock with Portland cement. The resulting powder when moistened makes a hard and durable cement that sets more slowly than Portland cement, and requires more water for setting.

Iron-Portland cement is a similar cement in which slag is one of the ingredients.

Callos is made by atomizing molten blast furnace slag against a spray of a weak solution of Epsom salt or some other alkali salt and then grinding the result and adding enough of an insoluble calcium salt to control the time of setting. The product hardens very quickly.

OCCURRENCE OF CEMENT ROCKS

Over a great portion of the country are impure limestones some of which might well be employed in making

[7] Bates, P. H., "High-alumina Hydraulic Cements," *Ind. Eng. Chem.*, Vol. 18, p. 554, 1926.

cement mixtures, but in most places the purer limestone necessary to raise the calcium content of the mixture to the minimum limit for this substance is lacking. The belts in which cement making is prominent, are limited to strips of country in which pure limestones are present.

One of the most important of these is the Lehigh Valley belt along the Lehigh Valley in Pennsylvania and its extension into New Jersey.[8] Here is made about 25% of all the cement manufactured in the United States.[9] The valley is underlain by argillaceous slaty limestone, under which is a bed of nearly pure Trenton limestone, and on the New Jersey side of the Delaware is an area underlain by the pre-Cambrian Franklin marble. The $CaCO_3$ of the Trenton bed varies between 80% and 97%, while the MgO_3 runs from 1.5 to 3%. The pre-Cambrian marble is still purer calcite. The area is near coal and the market, and is therefore favorably situated for the establishment of a successful cement industry.

The distribution of cement rocks and of cement plants is shown on maps in the Mineral Resources of the United States.

USES

The uses of cement are so many that it is impracticable to mention them all. In 1923 about 34% of the cement consumed was used in buildings, 24% for paving roads, 20.6% for various farm uses, 7% for making sidewalks, 5.2% was used by railways and the balance for miscellaneous purposes.[10]

[8] Peck, F. B., "Geology of the Cement Belt in Lehigh and Northampton Counties, Penna.," *Econ. Geol.*, Vol. 3, pp. 37–76, 1908.

[9] Burchard, E. F., and Bayley, B. W., "Cement in 1923," U. S. Geol. Sur., *Min. Res., 1923*, Pt. II, p. 306, 1924.

[10] Eckel, E. C., *Cements, Limes and Plasters*, 2nd ed. New York, 1914.

Eckel, E. C., "Portland Cement Materials and Industry of the United States, with Contributions by E. F. Burchard and Others," U. S. Geol. Sur., *Bull.* 522, 1913.

PRODUCTION

United States.—The number of active Portland cement plants in 1927 was 153, of natural cement plants 11, and of puzzolan cement only one—at Birmingham, Alabama, and their annual manufacturing capacity was about 227,000,000 bbls. of which about 75% was employed.[11] In this year the shipments were 174,023,051 bbls. valued at about $281,735,676. Of these all but 2,158,323 bbls. valued at $2,881,029, were of Portland cement. Of States making Portland cement, Pennsylvania led with 43,732,278 bbls., followed by California with a production of 14,580,654 bbls., Michigan with 13,965,241 bbls. and New York with 10,775,375 bbls.

The exports of cement during this year, most of which was Portland cement, were 816,726 bbls. valued at $2,796,717. Most of it went to Venezuela, Cuba, Panama and Mexico, but notable quantities went also to Uruguay, Colombia, Argentina, and Haiti.

The imports were 2,050,180 bbls. valued at about $3,000,000. Most of this came from Belgium, Denmark, Norway and the United Kingdom, and went to the Southern States and Porto Rico.

World.—Cement is made by all the countries of Europe. In Asia cement plants are active in China, India, Japan, Siam and Turkey. In Africa there are factories in Mozambique, and in South America there are factories in Brazil, Chile, Peru and Venezuela. Australia produces annually about 800,000 bbls., Canada about 10,000,000 bbls. In none of these countries outside of Europe, however, is the production equal to the consumption.

[11] A barrel of cement weighs 356 lbs. net.

CHAPTER XIX

MAGNESITE AND DOLOMITE

The most important sources of magnesium compounds are magnesite and dolomite, though recently a deposit of brucite ($Mg(OH)_2$) has been found near Luning, Nye County, Nevada, that may prove of commercial value.

MAGNESITE

GENERAL

Magnesite ($MgCO_3$) occurs in amorphous and crystalline varieties. The amorphous type forms a network of veins cutting serpentine. It is usually intersected by tiny veinlets of silica or is separated by layers of this substance from the serpentine in which the veins occur. Where the serpentine is brecciated its fragments are cemented by magnesite. This type of magnesite is produced by the action of either meteoric or magmatic water containing carbon dioxide upon the olivine of the rock from which the serpentine was derived, or upon the serpentine itself. In the latter case, the reaction is

$$H_4Mg_3Si_2O_9 + 3CO_2 = 3MgCO_3 + 2SiO_2 + 2H_2O$$

The making of the magnesite is attended by the production also of silica; consequently the magnesite of this kind is usually siliceous. Its best known occurrence is in lenses measuring 50 x 100 feet, on the islands of Lemnos and Eubœa,[1] Greece, where it has been worked for a long time.

[1] Boydell, H. C., "The Eubœan Magnesite Field," *Eng. and Min. Jour.*, Vol. 112, No. 20, pp. 771–776, 1921.

An analysis[2] of an average of 2,500 tons of crude Grecian magnesite gave:

MgO	CaO	CO_2	Fe_2O_3	Al_2O_3	SiO_2		Total
46.94	.55	51.10	.55	.55	.86	=	100.55

One form of the crystallized magnesite usually occurs as lenses in limestones and dolomites from which it may have been derived by the action upon them of hot water emanating from igneous magmas. Crystallized magnesite is found also in small quantity along the borders of amorphous veins in serpentine.

A second crystalline variety occurs as sedimentary beds, possibly formed in salt lakes, interlayered with other sedimentary rocks. This is not a typical magnesite, since nearly all deposits of this kind contain 10% or more of calcium carbonate.

A third type of crystalline magnesite is found as fissure veins, which are supposed to be of magmatic origin. Because this type contains much iron it is of little value.[3]

The largest deposits of crystalline magnesite are in Hungary (now partly in Czechoslovakia and partly in Austria) where it is a replaced dolomite, from which about 150,000 tons are produced annually.

Pure magnesite is white or yellowish, and the massive amorphous forms are fine-grained, resembling unglazed porcelain, and is very brittle. Massive crystalline forms resemble coarse-grained limestone and may be of any color.

USES

Crude magnesite is employed in making toilet and medicinal preparations, in the manufacture of boiler coverings, of compounds used in paper making, as an

[2] Ladoo, R. B., *Non-metallic Minerals*, New York, p. 325, 1925.

[3] Bain, G. W., "Types of Magnesite Deposits and Their Origin," *Econ. Geol.*, Vol. 19, pp. 412–433, 1924.

absorbent for dynamite and in the manufacture of hydrochloric acid, of carbon dioxide, of magnesium salts, and of the metal, magnesium.

The dead burned material, calcined at 1400–1700° C., is made into refractory bricks and fire-proof paints.

Light burned magnesite, heated to 600–800° C. is employed under the name of "plastic magnesia" for inside and outside stucco.

Magnesite, wholly or partially changed to the basic carbonate or to the hydroxide, is used for heat insulation, fire proofing, in cosmetics, for refining sugar, as a dry cleaner, in prevention of boiler scale, as a varnish dryer, in the manufacture of crucibles, and as a filler in rubber.

Partially burned material, containing 3 or 4% of CO_2 is mixed with $MgCl_2$ and made into Sorel cement by wetting the finely ground, partially calcined material with a solution of magnesium chloride. In a short time this mixture will set as an extremely hard and strong mass. The commercial cement has mixed with it ground cork, sand or some other filler which diminishes its weight and decreases its cost. The cement is used mainly for floors of hospitals, offices, etc., as it does not crack or grind to dust, is smooth, takes color well and may be polished by oiling or waxing.

Partially calcined magnesite is used also as an accelerator in the vulcanization of rubber for tires, and in the manufacture of magnesium.[4]

OCCURRENCE

United States.—In the United States amorphous magnesite is found in largest quantity along the Coast Ranges in California and the crystalline variety in Stevens County, Washington.

[4] For a discussion of the rapidly increasing use of magnesium in metallurgical processes and in alloys with aluminium see the volume *Magnesium*, American Magnesium Corporation, Niagara Falls, New York, 1923.

In California[5] it occurs, mainly in the Coast Range and on the west slopes of the Sierras, as veins in Lower Cretaceous serpentines that are much fractured and faulted. The material is much like that in Greece. A good specimen on analysis gave:

MgO	CaO	CO_2	Fe_2O_3	Al_2O_3	SiO_2
46.61	.40	51.52	.21	.14	.73

In Washington,[6] near Chewelah in Stevens County, the magnesite is like that in Hungary and is used for the same purposes. Like that in Hungary it is a replaced dolomite. It is probably pre-Cambrian. The material looks very much like a coarse-grained white, black, pink or red marble. It is of excellent quality and the deposits are large. Several are known to contain 1,000,000 tons each.

A large deposit of magnesite is known to occur also near St. Thomas, Clark County, Nevada,[7] but it has not yet been developed. It occurs in tilted beds, in some places over 200 feet thick, between beds of conglomerate, sandstone and shale. The rock contains 36.5% of MgO and about 5% of CaO.

Other countries.—Important deposits of magnesite are known also near Grenville in Argenteuil County, Quebec.[8] Here the magnesite is in lenticular masses associated with dolomite. The two rocks are in a folded and faulted schist series cut by serpentine. The best rock contains less than 21% $CaCO_3$.

The largest and most available deposits known are

[5] Hess, F. L., "Magnesite Deposits of California," U. S. Geol. Sur., *Bull.* 355, and Gale, H. S., "Late Developments of Magnesite Deposits in California and Nevada," U. S. Geol. Sur., *Bull.* 540, pp. 483–520, 1913.

[6] Whitwell, G. E., and Patty, E. N., "The Magnesite Deposits of Washington," Washington Geol. Sur., *Bull.* 25, 1921.

[7] U. S. Geol. Sur., *Min. Res., 1920,* Pt. II, pp. 11–12, 1921.

[8] Bain, G. W., "Magnesite Deposits of Grenville, Quebec," Amer. Inst. Min. Met. Eng., *Trans.*, Aug. meeting, 1923.

those in Austria, in Czechoslovakia and on the Grecian islands, already referred to. Large deposits occur also in Venezuela, Russia, Manchuria[9] and the Transvaal.[10]

PRODUCTION AND IMPORTS

UNITED STATES.—In 1927 the production of magnesite in the United States was 121,490 short tons valued at $1,090,550. Of this amount 43,750 tons came from California and 77,440 tons from Washington.

There were imported 59,368 short tons of calcined magnesite and 856 tons of crude material with an aggregate value of $959,483. Most of this came from Austria, Czechoslovakia, and India.

WORLD.—The world's production of magnesite in 1926 was about 525,000 metric tons. The largest producers were:

	Metric Tons
Austria	162,959
United States	121,109
Russia	103,017
Greece	95,638
Czechoslovakia	83,135
India	30,950
Italy	19,842
Australia	10,754

RESERVES

It is estimated that the reserves of commercial magnesite in the United States[11] are 3,000,000 tons in Washington and 1,000,000 tons in California. About 120,000,000 tons are in Hungary, 5,500,000 tons in Greece

[9] Niinomy, K.. "Magnesite Deposits of Manchuria," *Econ. Geol.*, Vol. 20, pp. 25–53, 1925.

Nishihara, H., "An Enormous Magnesite Deposit in Manchuria." *Eng. and Min. Jour.-Press*, Vol. 119, pp. 488–499, 1925.

[10] Trevor, T. G., "Base Metal Resources of South Africa," *So. Af. Min. Jour. of Indus.*, July, 1924.

[11] U. S. Geol. Sur., *Min. Res., 1919*, Pt. II, pp. 15–16, 1920.

and 3,200,000 tons in Venezuela.[12] For many purposes a high grade magnesium dolomite may be substituted.

HYDROMAGNESITE

Hydromagnesite is the hydrated basic carbonate, $Mg_2(MgOH)_2(CO_3)_3.3H_2O$, occurring in loose chalk-like masses. While it may be used for the same purposes as magnesite its high content of water is objectionable. Deposits are known in the Atlin mining district, British Columbia, that consist of beds of fine powdery material 6 or 8 feet thick. Some is said to have been used in Vancouver for the manufacture of plastic magnesite.

DOLOMITE

Dolomite ($MgCa(CO_3)_2$) is widely distributed in large quantities in bedded formations with limestone and other sedimentary rocks. It may be formed by direct precipitation from solution, or, more commonly, by a replacement of limestone in which a portion of the calcite has been taken by magnesium carbonate through the agency of percolating water. In some places magnesian limestone is partially dissolved, losing its more soluble calcite and thereby become richer in magnesium carbonate.

The theoretical composition of pure dolomite is 30.4% CaO, 21.9% MgO and 47.7% CO_2, or 54.2% $CaCO_3$ and 45.8% $MgCO_3$, but most dolomites contain small quantities of iron, manganese, aluminium and silicon. With increase in the proportion of magnesium the rock gradually approaches magnesite in composition and may be used for some of the purposes for which this material is best suited.

Most dolomite is finely or coarsely granular like ordinary limestone, but metamorphosed forms are marbleized.

[12] *The Magnesite Industry*, p. 18, U. S. Tariff Commission, 1920.

Most of the dolomite quarried in the United States is used as building stone, stucco and terrazzo, as a flux in blast furnaces or open-hearth furnaces, as a refractory furnace lining, or is burned to make high magnesia lime. Since the beginning of the war, however, a considerable quantity of dolomite has been mined for the uses to which magnesite was formerly put. In 1927, the quantity mined for these purposes was 1,355,000 short tons. Of this tonnage, 374,415 tons was dead-burned by the producers. This quantity together with 434,160 tons of crude rock, that was sold for dead-burning by its purchasers, was all employed in making refractory products. Partially calcined rock made from 69,940 tons of crude rock was used in making pipe and boiler coverings. High magnesium lime weighing 50,000 tons was sold to sulphite paper mills and in 1926, 16,520 tons of high grade crude dolomite valued at $31,424 was employed in making carbon dioxide. A small quantity was used in making Epsom salt and other magnesium compounds.

Dolomite is so widely distributed throughout the world that a recital of its occurrences is impracticable. High grade rock is mined in Georgia and several other States as a source of magnesium compounds. The Georgia occurrences are beds of fine-grained white marble interlayered with coarse-grained white marble in a metamorphosed Cambrian series at Whitestone in the northwest part of the State. Similar rocks occur also a little farther south, but they have not yet been developed. The Whitestone dolomite contains 37% $MgCO_3$ and 58% $CaCO_3$ and samples from deposits in Pickens County, Georgia, contain 43% $MgCO_3$ and 55% $CaCO_3$.

MAGNESIUM AND MAGNESIUM SALTS

Magnesium.—The metal magnesium is employed in the form of ribbon and powder for the production of light,

and as ribbon and wire in the degasification of radio tubes and thermos bottles. The metal is also used in alloys and for the manufacture of parts of machines that must be light in weight, like the steering wheels of airships, etc.

Most of the metal is made from magnesite.

The total production of magnesium and magnesium powder in the United States during 1927 was about 366,400 lbs. valued at about $441,700. The imports were 7,131 lbs. with a value of $8,402.

Magnesium chloride and sulphate.—Magnesium chloride and magnesium sulphate (Epsom salt) are obtained from the bittern waters of salt works and the sulphate, in addition, from a dry lake deposit near Oroville, Washington. In 1927, however, the Oroville deposit was not worked.

Epsom salt is used in tanning leather and as a medicine. It is also employed in sizing and loading cotton goods, in weighting silk, paper, etc., in enameling, fireproofing, and in the manufacture of paints and soaps. The chloride is used mainly in the manufacture of Sorel cement. It is also used as a dressing for cotton goods, in a fire-resisting paint, as a drying agent, in the manufacture of magnesium and the oxide, and in making hydrochloric acid and solutions for killing weeds.

In 1926, both salts were produced in California and Michigan, and a small quantity of the sulphate was obtained from the lake beds at Oroville.

Table LXXII.—Production of Natural $MgCl_2$ and $MgSO_4$ in the United States During 1926

	Lbs.	*Value*
Magnesium chloride	52,569,000	$701,580
Magnesium sulphate	23,991,000	339,320

In 1927 the total production of both salts was 69,764,000 lbs., valued at $1,169,150.

The imports in 1927 were:

TABLE LXXIII.—IMPORTS OF $MgCl_2$ (HYDROUS AND ANHYDROUS) AND OF $MgSO_4 + 7H_2O$ (EPSOM SALT), IN 1927

	Lbs.	*Value*
Magnesium chloride	8,185,363	$59,950
Epsom salt	11,620,675	60,527

Natural magnesium sulphate occurs in and around lakes in Wyoming, Utah, California, British Columbia and in the salt deposits at Stassfurt, Germany.

The principal magnesium salt in the Stassfurt deposits is kieserite ($MgSO_4.H_2O$). This is washed with water to remove the magnesium and sodium chlorides that may be associated with it. The resulting sulphate is dissolved in hot water and crystallized. During the process it is hydrated to Epsom salt.

OTHER MAGNESIUM SALTS.—Besides the two salts produced from natural sources there are also manufactured in the United States large quantities of the same salts and some others. In 1924 the value of these products was over $3,000,000. They were made from magnesite, dolomite and the crude chloride and sulphate.

TABLE LXXIV.—PRODUCTION OF MANUFACTURED MAGNESIUM SALTS IN 1924

	Lbs.	*Value*
Epsom salts	41,351,136	$851,103
Magnesium oxide	13,193,112	707,975
Magnesium chloride	52,065,600	815,398
Other magnesium salts	1,176,125	549,790

The imports of calcined magnesia (magnesium oxide) in 1927 amounted to 259,357 lbs. valued at $48,093, and of the carbonate 348,383 lbs. valued at $20,115. Before the war nearly all the magnesium compounds used in the United States were imported from Germany.

CHAPTER XX

GRAPHITE

GENERAL

Graphite occurs in two forms, flake, or crystalline, and amorphous. The first is in crystalline flakes and is very pure. The second is earthy and is often quite impure. For most purposes the amorphous variety should contain 90–95% C, but for some purposes as, for instance, in the manufacture of paint where color only is the desideratum, material containing as little as 35% C is acceptable.

Crystalline graphite occurs as flakes in pegmatite and other igneous rocks, in veins of massive material cutting igneous and metamorphic rocks, and disseminated as small plates through crystalline schists and contact metamorphosed sediments, especially limestones.

The amorphous form is found largely in dynamically metamorphosed sediments, like slates. In a few places, as in Mexico, it results from contact metamorphism of coal.

ORIGIN

The amorphous graphite and much of the crystallized variety in schists is probably the result of the alteration of carbonaceous material that was laid down in sediments. The flake and vein graphite and that in contact rocks may have originated in the cooling of a magma charged with carbon monoxide and hydrogen, since these react at about 800° as follows:

$$2CO + H_2 \rightleftarrows 2C + H_2O$$

However, it is possible that in some cases the igneous rocks have caught up carbonaceous material in their

ascent to the surface and decomposed it, producing among other things carbon which upon the cooling of the magma separated out as graphite, much as graphite may be formed in molten iron.

USES

The principal uses of graphite are in the making of crucibles, lubricants, pencils, paint, electrodes, dynamo and motor brushes and stove polish. Finely ground flake graphite is also used in boilers to prevent the formation of scale, and as a dusting agent for electrotyping. It is employed to polish powder and shot and as a filler for dry batteries and for many other minor purposes.

The best grade of crystalline graphite is Ceylon lump which is a sorted product containing about 90% C. Chip is in finer particles and contains about 80% C, and dust contains about 70% C. The bulk of Ceylon lump and chip is used for making crucibles. Dust and other grades of graphite are used as lubricants, in pencils and paints, for foundry facings, in stove polish, for making electrodes, fillers for dry batteries and steam boiler mixtures.

Amorphous varies, which may contain as low as 35% graphite, may be used for almost any purpose for which the crystalline variety is employed except the manufacture of crucibles.

High grade Mexican amorphous graphite contains about 86% of graphite. It is used largely in making pencils, for foundry facings and lubricants.

In 1924 the natural graphite consumed in this country was distributed among the following articles.

	Per Cent		*Per Cent*
Crucibles	13	Commutator brushes	5
Foundry facings	52	Stove polish	1.5
Pencils and paints	21	Lubricants	1.3

COMPOSITION

The composition of some typical commercial crucible graphites is shown in the following table.

TABLE LXXV.—COMPOSITION OF HIGH-GRADE COMMERCIAL GRAPHITE FROM DIFFERENT LOCALITIES

	Volatile Carbon	*Graphitic Carbon*	*Ash*
Ceylon	5.10	79.40	15.50
Ceylon	1.68	85.06	13.25
Cumberland, England	1.10	91.55	4.85
Ural Mountains	.72	94.03	5.25
Ticonderoga, N. Y.	.82	97.42	1.76
Southern Australia	2.15	25.75	72.10
Madagascar	5.18	70.69	24.13
Passau, Bavaria	4.20	73.65	22.15
Alabama	2.66	81.82	15.51
Alabama	1.31	91.18	7.37

PRODUCTION

UNITED STATES.—In 1927 the sales of domestic graphite in the United States were 2,595 short tons of the amorphous variety, valued at $35,850 and 5,224,400 lbs. of the crystalline variety valued at $197,121. In 1918 the corresponding quantities were 6,560 tons valued at $69,455 and 12,861,839 lbs. valued at $1,454,799. Alabama, New York, and Pennsylvania were the largest producers of crystalline graphite in 1918, but in 1927 only Alabama, California, Montana and Texas produced any. Amorphous graphite was mined in Rhode Island, Michigan, and Nevada. Rhode Island was the largest producer of amorphous graphite and Alabama the largest producer of the crystalline variety.

The production of crystalline graphite was greatly stimulated by the war; that of the amorphous variety was only slightly increased. After the war ended large

stocks of the crystalline variety had to be disposed of before mining could be resumed at a profit. Consequently, the production of both varieties has languished during recent years. Moreover, artificial graphite made from anthracite coal and from petroleum coke now competes with the natural amorphous product. This is used in the manufacture of electrodes, lubricants and paints, displacing an equal amount of the natural graphite. During 1927 12,257,239 lbs. were manufactured.

Imports of natural graphite in 1927 were 17,452 tons valued at $723,923. Of this about 9,560 tons were of the amorphous variety.

The importations of crystalline graphite were contributed mainly by Ceylon, Madagascar, Canada and France and those of the amorphous variety by Mexico and Chosen. In 1918 the imports were valued at $3,092,475 and in 1917 at $8,961,988.

Exports of graphite and manufactures of graphite exclusive of crucibles were valued at $435,997. The value of pencils and pencil leads exported in 1926 was $2,144,614 and of crucibles (mostly graphite) $149,456.

Other countries.—The most important producing countries during 1926 were:

Table LXXVI.—Production of Natural Graphite in 1926
(In Metric Tons)

Czechoslovakia	30,818	Italy	7,300*
Chosen	18,692	Mexico	5,837*
Austria	14,756	Russia	5,207
Madagascar	14,329*	United States	4,724*
Germany	14,304	Canada	2,474
Ceylon	13,091*		

Total of all countries (estimated) 95,000.

* In 1927.

OCCURRENCE

United States.—Crystalline, or flake, graphite occurs widely spread over the crystalline areas of Canada, New

England, the Appalachian and the Rocky Mountain States and in Texas, but only in a few places in large enough quantity to be of commercial value. The best known deposits are in the Adirondacks[1] where the graphite occurs in pegmatites, as tiny veins in gneiss, and as tiny flakes scattered through metamorphosed quartzites and marbles (Fig. 118).

At the Dixon Mine, near Lake George, which was for a long time one of the largest producers of this kind of graphite, a schistose quartzite that contains 6½% of graphite was mined. This was crushed and washed repeatedly and the resulting product was used in making pencils and crucibles. A similar occurrence has been worked at Annandale in New Jersey. The graphite at this place occurs in large flakes in pegmatite and in small scales disseminated through gneiss at its contact with the pegmatite. The mineralized zone is reported to be ten feet wide and to contain 11% of carbon. The mine at this place was abandoned about 40 years ago, but in 1927 the deposit was opened again.

In Alabama crystalline graphite occurs in granites and schists in a zone 10 miles long and 100 or more feet wide, and in an amorphous graphitic clay in slightly metamorphosed Paleozoic crystalline schists. The granites, which are deeply weathered, contain 4.5% of graphite which is separated by washing.[2]

In Texas the deposits are in the central part of the State in a siliceous schist containing 6%–10% of graphite.

Vein graphite is mined near Dillon, Montana.

Amorphous graphite is widely spread. At Cranston, near Providence, and at Tiverton, Rhode Island, graphitic shales 30 feet thick and containing about 50% carbon,

[1] Alling, H. L., "The Adirondack Graphite Deposits," N. Y. State Mus., *Bull.* 199, 1918.

[2] Jones, W. P., "Summary Report on Graphite," Geol. Sur. of Ala., *Circular* 9, 1929.

FIG. 118.—Map of principal graphite deposits of the world. (*After H. G. Ferguson, U. S. Geol. Sur., Min. Res., Pt. II, Pl. II, 1921.*)

are interbedded with metamorphosed carboniferous sandy layers.

Other countries.[3]—Amorphous graphite is very generally distributed throughout the world, but in most places is too impure to compete with that from Mexico and Italy.

At the Santa Maria Mines, in Sonora, Mexico, are 7 beds of graphite averaging about 86% of carbon. They are interbedded with metamorphosed Triassic sediments, which are folded and cut by granite dikes. The graphite represents coal beds which in other parts of the State are found in the form of coke, anthracite and bituminous coal. The mines are probably the largest amorphous graphite mines in the world.

The Italian deposits are on the east flank of the Alps, in Turin, in the Ligurian Mountains, in Genoa and in the Province of Cuneo. The graphite grades into anthracite from which it was made.

Amorphous and crystalline graphite occur also in large amounts in Lower Austria, in Southern Bohemia, and in Moravia, where it comprises lenticular masses of graphitic schist interbedded with other metamorphic schists. The graphitic zones in Lower Austria, near the Danube River, are from 6 to 45 feet thick. As mined the rock contains from 30% to 55% carbon, which by washing is concentrated to about 60%.

Other deposits in the Styrian Alps, are of amorphous graphite, produced by the metamorphism of coal beds in a series of closely folded schists. The graphite beds vary in thickness up to 48 feet. They furnish a crude ore containing from 40% to 95% carbon. Some of it enters the market in its natural state, without concentration. There

[3] For an excellent summary of the graphite resources of the world see, Ferguson, H. G., "Graphite," U. S. Geol. Sur., *Min. Res., 1918*, Pt. II, pp. 223–265, 1921, and Cirkel, F., "Graphite, Its Properties, Occurrence, Refining and Uses," Can. Dept. of Mines, Mines Br., Ottawa, 1907.

appears to be a large quantity in reserve in these countries, but it is of comparatively low grade, useful mainly for foundry facings, paint and for cheap lubricants.

Large deposits of amorphous graphite also occur on the southern slopes of the Carpathians in Rumania, on the Yenisei River in Eastern Siberia, in Chosen, in the northern part of the Caucasus Province and at many other places in Russia, and in French Indo-China. Some of them are reported to be of great size but details concerning them are lacking. In the Yenisei district in Russia intrusions of trap have altered Permian and Upper Carboniferous coal beds.

In Chosen amorphous graphite occurs in beds and irregular lenses of considerable size in the Central and Eastern part of the country.

Flake graphite is much less common than the amorphous variety. Besides the deposits in the Adirondacks, in which there are estimated to be 300,000,000 tons of available material, there are also large deposits in several countries in Europe, Asia and Africa.

Flake graphite occurs in the Passau district in Bavaria in gneissic layers 30 to 60 feet thick. The graphitic portions of the gneiss constitute lenses that contain from 20 to 25 per cent of graphite. At the Alibert mine near Irkutsk in Siberia is an excellent grade of the mineral that has been used in making pencils and crucibles. In Spain a belt 10 miles long and half a mile wide in Huelva Province contains numerous lenses of graphitic schists containing 10 to 20% of good material. In Cumberland, England, is the well-known Borrowdale deposit, which for hundreds of years furnished excellent graphite for pencils. In Canada both flake and lump graphite have been found on the south shore of Baffin Island, but the most noteworthy deposit is in Renfrew County, Ontario, where the ore is a schist containing from 60% to 80%

graphite in a 40 foot layer standing vertically between crystalline limestones. Graphitic limestone, with from 10% to 15% graphite occurs in Haliburton, Hastings, and in Lanark counties in Ontario and in Labelle County, Quebec.

The great reserves of crystalline graphite are however in Ceylon and Madagascar.

In Ceylon[4] the graphite industry is said at one time to have employed about 50,000 natives (Fig. 119). The graphite occurs mainly in the southeastern part of the island, partly as scales disseminated through an interbedded series of gneisses and crystallized limestones, but mainly in veins cutting these rocks. The width of the veins varies between an eighth of an inch and several feet. In the smaller veins the graphite is an aggregate of parallel platy needles perpendicular to the vein walls, but in larger ones it is in rather coarse plates. Quartz and pyrite are present in small quantity in most veins and in some are present also biotite, orthoclase, pyroxene, apatite, allanite and rutile. None of these minerals are abundant, and from some of the veins they are entirely absent.

The graphite appears to have been deposited from solutions following fracture planes in rocks, but as to the source of the solutions nothing is yet known.

The Ceylon graphite has long been the favorite for making crucibles.

For many years Ceylon (Fig. 120) was the premier graphite producer of the world, but recently Madagascar has become preeminent. Madagascar graphite,[5] which is of excellent quality, occurs in schist and gneiss throughout the entire area of crystalline rocks which cover over two-thirds of the surface of the island. The schists are

[4] Bastin, E. S., "The Graphite Deposits of Ceylon," *Econ. Geol.*, Vol. 7, pp. 419–443, 1912.

[5] Shelley, J. W., "Graphite in Madagascar," *Min. Mag.*, Vol. 14, pp. 324–330, 1916.

apparently feldspathic quartz schists with flakes of graphite lying between the quartz grains as at the Dixon mine

FIG. 119.—Sketch map of Ceylon, showing locations of graphite deposits, (*Adapted from Stonier by Bastin, U. S. Geol. Sur., Min. Res., 1911, Pt. II.*)

in the Adirondacks. Another method of occurrence is in flat veins lying parallel to the foliation of the gneisses. Since the weathering is deep the rock is easily worked.

FIG. 120.—Sketch map of Madagascar showing locations of graphite pits. (*Adapted from Constanciel by Ferguson, U. S. Geol. Sur., Min. Res., 1918, Pt. II.*)

In the lowlands where weathering is more complete than in the plateau districts, the graphite occurs in soil overlying the rocks, but because of the difficulty of transporta-

tion through the lowland jungles, however, most of the mines are on the plateaus.

The graphite tenor of the ore is about 25%, but 10% ore is considered workable. It is estimated that there are 2,000,000 tons of merchantable graphite in sight at developed properties that are capable of being mined by open cuts, and 7,000,000 additional tons that can be reached by underground methods above a depth of 325 feet.

Workable flake graphite deposits are also reported to occur in the Transvaal, in South Australia, in New South Wales and in New Guinea.

The reserves of both amorphous and flake graphite are sufficient to last the world for many years.

CHAPTER XXI

MICA

Mica is obtained mainly from pegmatites. It is widely spread in other rocks but usually in such small pieces as to be valueless for the purposes for which most mica is employed. The main value of mica depends upon its easy cleavage, by which thin plates may be produced, and upon the fact that it is a non-conductor of heat and electricity.

VARIETIES

Only two minerals are produced as micas, muscovite and phlogopite, or amber mica, but two others are mined in some places as sources of chemical compounds—lepidolite as a source of lithium and roscoelite as a source of vanadium. Other members of the mica group or rocks containing large proportions of mica, and certain other platy minerals that resemble the true micas in their platy character and their easy cleavage are mined for other purposes than those for which muscovite and phlogopite are mainly employed, but not in large quantities. Among these are (1) sericite, a fine scaly muscovite, constituting an important component of certain schists, (2) chlorite, a dark micaceous mineral that cleaves into plates that are non-elastic, (3) chlorite schists, and (4) vermiculite and jefferisite. The last two are closely related to the chlorites. Their color varies from white to yellow, brown or green, and their cleavage laminæ are soft and flexible. The chlorites and biotite are iron-magnesium alumino-silicates, whereas muscovite is an alkali-alumino-silicate.

Muscovite.—Muscovite occurs in pegmatites in large groups of crystals, known as books: as a rule but 10% or 15% of the mineral can be obtained from the rock quarried, and of this but 15% can be cut into shapes. The rest is scrap, which is ground. A small quantity of scrap mica, which is, in some cases, so finely divided as to be sold as ground mica, is obtained from weathered mica schists and as a by-product in the purification of kaolin, and in the production of feldspar.

The value of a mica deposit depends upon the abundance and size of the books, as large plates are much more valuable than smaller ones, upon the perfection of the cleavage of the masses in the books, their color and transparency and their freedom from inclusions. The perfection of cleavage may be injured by "A" structures, which are striations inclined to one another and by herring-bone structures and rulings, which are parallel striations on the cleavage surfaces.

Muscovite is sold as sheets, splittings, and ground mica. The smallest sheets known as "punch mica" must yield a circle 1½ inches in diameter to be of value. Circle mica should yield a disc about 2 inches in diameter. These are used as insulators in electric-light bulbs, etc. The smallest "plate sheet" must cut to 1½ x 2 inches. The largest sheets commonly used measure 8 x 10 inches, although in late years there has been an increasing demand for plates that will furnish an 18-inch circle, for use in theatrical transparencies for projection. In 1925 the prices varied from 9 cents per lb. for punch mica, and 23 cents per lb. for small rough sheets 1½ x 2 inches, to $7.50 per lb. for large rough sheets 8 x 10 inches.

Sheet mica is used for electrical insulation, for glazing stoves, for making lamp chimneys and for phonograph and radio diaphragms and radio condensers.

Splittings are very thin sheets (1/1000 in.±) that are

built up into mica board, micanite, etc. No appreciable quantity of splittings is produced in the United States, nearly all being imported. Micaboard is used mainly for electrical insulation.

Ground mica is used in the manufacture of roofing, in lubricators for wood axles, in the annealing of steel and in decoration—as in wall paper, and fancy paints. It is also made into insulators for boilers, etc., and is employed as a filler for rubber goods and asphalt and as an absorbent for nitroglycerine. In India it is used as a medicine.

Most ground mica is made from the scrap trimmed from the crude masses in the production of sheet mica and from material that is rejected as being unfit to cut. Small quantities are recovered in the preparation of kaolin and feldspar. Much of this is already finely enough divided to be employed without grinding. In 1927 the production of ground mica in the United States amounted to 11,585,383 lbs. valued at $423,479.

The consumption of the ground mica used in 1927 was distributed as follows:

	Per Cent		*Per Cent*
Roofing	22	Fancy paints and "snow"	18
Wall paper	33	Electrical insulation	18
Rubber	27	Lubrication	18

Mica schist.—Because the supply of scrap mica for grinding is not always sufficient to meet the demand the schists that are rich in muscovite and biotite have been utilized to supply the lack. The resulting product though not pure can be used for roofing and for many other purposes for which ground scrap mica has heretofore been employed. In 1927 mica schists of both kinds were mined and crushed at Spruce Pine, North Carolina, for use as roofing material.

PHLOGOPITE.—Amber mica has some special uses to which white mica is not adapted. It is especially valuable as washers between the moving parts of dynamo-electric machinery, because its abrasive coefficient under the conditions under which it functions is the same as that of copper, and it is now being employed successfully in goggles for use during oxyacetylene welding. All used in the United States is imported from Canada.

PRODUCTION AND IMPORTS

UNITED STATES.—The total production of muscovite in the United States during 1928 was valued at $363,600, divided as follows:

TABLE LXXVII.—MICA SOLD BY PRODUCERS IN THE UNITED STATES DURING 1928

	Weight	*Value*
Sheet mica	1,620,000 lbs.	$259,200
Scrap mica	5,800 tons	104,400

North Carolina and New Hampshire are credited with 95% of the entire amount of sheet mica sold in 1927 and 72% of the scrap mica. New Mexico and South Dakota produced most of the remaining quantity.

TABLE LXXVIII.—PRODUCTION OF MICA BY TWO STATES IN 1927

	Sheet	*Scrap*	*Total Value*
North Carolina	665,360 lbs.	2,995 tons	$165,019
New Hampshire	720,219 lbs.	1,284 tons	101,758

The imports of all kinds of mica in 1927 are shown in the following table on page 438.

TABLE LXXIX.—MICA IMPORTED FOR CONSUMPTION IN THE UNITED STATES DURING 1927

	Lbs.	*Value*
Uncut sheets	776,307	$ 399,302
Cut	64,075	75,469
Ground	.....	.....
Splittings	2,588,253	1,123,808
Manufactured	31,012	31,730
Total	3,459,647	$1,630,309

The principal countries from which the imports came were:

	Pounds	*Valued At*
India	2,043,394	$868,637
Canada	596,693	227,755
United Kingdom	230,609	142,370
France	249,421	155,738
Argentina	60,866	28,006

The exports in 1927 were 2,867,798 lbs. with a value of $207,263. Most of it went to Canada, England and France in the order named.

WORLD.—The world's production of mica during 1927 is not yet known. In 1926 it was about 17,000 metric tons. The principal countries contributing to the output were:

	Metric Tons		*Metric Tons*
United States	7,374	Transvaal	872
Canada	2,309	Madagascar	276
British India	4,569	Southern Rhodesia	166

OCCURRENCE

UNITED STATES.—The principal sources of muscovite in the United States are the pegmatites of the mountain

districts in Western North Carolina,[1] in New Hampshire, in other of the Appalachian States and elsewhere, especially in the Black Hills [2] and the Rocky Mountain States, particularly New Mexico, but the mineral is known to occur also in commercial quantities in Idaho, Nevada, Texas and Colorado.

Other countries.—In Canada muscovite is abundant throughout the areas of crystalline rocks in Ontario, Quebec and the Rocky Mountain region, but only a few of the occurrences are worked. The mineral is mined irregularly in the area south and west of Ottawa and at North Hastings near Bancroft. At North Hastings some single crystals of muscovite are reported to have weighed two tons.

Phlogopite is obtained from just north of Ottawa between the Gatineau and Lievre rivers in Quebec and in the eastern part of Ontario north of Kingston (Fig. 121). The mineral forms part of a coarse dike rock composed of pyroxene, apatite, calcite and enormous phlogopite crystals, and it occurs also as a metamorphic mineral in the limestone through which the dike cuts.[3]

The total production of mica in Canada during 1926 was 2,451 short tons valued at $222,825.

The commercial deposits in India,[4] which furnishes about 70% of the world's sheet mica, are at the Kodarma mines in Bengal and in the Nellore district, Madras, where about 15,000 natives are employed in mining, cutting and splitting the mineral. Because of their long

[1] Sterrett, D. B., "Mica Deposits of Western North Carolina," U. S. Geol. Sur., *Bull.* 315, pp. 400–422, 1906, and "Mica Deposits of North Carolina," *Bull.* 430, pp. 593–638, 1910.

[2] Sterrett, D. B., "Mica Deposits of South Dakota," U. S. Geol. Sur., *Bull.* 380, pp. 382–397, 1908, and "Some Deposits of Mica in the United States," *Bull.* 580, pp. 65–125, 1915.

[3] De Schmid, H. S., "Mica, Its Occurrence, Exploitations and Uses," Can. Dep. Mines, Mines Br., *Pub.* 118, 1912.

[4] Am. Inst. Min. Eng., *Trans.*, Vol. 45, p. 94.

experience in preparing it, the Indian mica is considered the best on the market.

Guatemala, Brazil, Bolivia and Argentina possess large deposits of mica that are only partly developed, and other countries in Central and South America are known to contain valuable deposits that are undeveloped. In 1926

Fig. 121. Lacy phlogopite mine, Loughboro Twp., Frontenac Co., Ontario. (*Courtesy of Mines Br., Can. Dept. of Mines, Ottawa.*)

Argentina sent $63,000 worth of the commodity to the United States, Brazil $48,400 worth and Guatemala crude, cut and split mica to the value of $14,500.

In Africa commercially valuable deposits are known in Abyssinia, Union of South Africa, Rhodesia, Tanganyika and Madagascar and in all of them small quantities of the mineral have been mined. The Madagascar deposits are especially interesting because much of the mineral is the

amber variety (phlogopite). The phlogopite deposits are near Fort Dauphin and are like those in Canada in that the associated minerals are pyroxene and calcite. In 1926 Madagascar exported 455 metric tons of various micas having a value of about $225,000.

In Tanganyika the muscovite in some pegmatites measures 3 feet by 3 feet in the rough and furnishes sheets 18 inches across. The dikes are scattered over the southern and eastern portions of the country in and around the Ulugura Mountains.

Many other countries in Europe and Asia are known to contain mica in abundance, but only those in Siberia promise to yield a large product under present economic conditions.

With the rapid increase in the use of electricity it is probable that there will be a largely increased demand for mica, with the result that many deposits now idle will soon become productive.

VERMICULITE

Zonolite is a vermiculite, which is probably an altered phlogopite. It is dark and opaque, is brittle and lacks the perfect cleavage of unchanged mica. When heated it exfoliates or expands to about 15 times its original volume, enclosing innumerable air bubbles. Consequently it becomes an excellent insulating material for steam pipes, refrigerating equipment, wall board, and a good lightweight filler for cements.

Vermiculite occurs in commercial quantity near Libby, Montana, near Salida, near Hecla and near Iola in Colorado. At Libby it occurs in a dike 100 feet wide and at least 1,000 feet long, composed mainly of pyroxene and biotite, or its alteration product, vermiculite.[5]

[5] Pardee, J. T., and Larsen, E. S., "Deposits of Vermiculite and Other Minerals in the Rainy Creek District, Near Libby, Montana," U. S. Geol. Sur., *Bull.* 805-B, 1929.

JEFFERISITE

Jefferisite is not clearly distinguished from vermiculite. The two are similar in composition and are employed for the same purposes. Seven miles east of Westcliffe, Custer County, Colorado, is a mass composed of quartz, hornblende, chlorite, magnetite and 50% jefferisite, from which some of the last-named mineral has been prepared and put on the market.

CHLORITE SCHISTS

Chlorite schists are abundant in schist series where they have been formed by the metamorphism of basic igneous rocks and some kinds of slates. They are crushed and used for terrazzo and in the manufacture of roofing and hard rubber goods, foundry facing, etc.

The material is mined regularly near Canton, Georgia, where the chlorite is said to be chiefly clinochlore.

CHAPTER XXII

FLUORITE AND CRYOLITE

FLUORITE

USES

Fluorite (CaF_2) is consumed mainly as a flux in basic open-hearth steel furnaces and to a less extent in iron blast furnaces, iron foundries, in gold, silver, copper and lead smelters, in the manufacture of glass, enamel and sanitary ware, in the preparation of hydrofluoric acid and in the refining of antimony and lead, and in the electrolitic production of aluminium. It is used also to a slight extent in bonds for emery wheels, and in the recovery of potash from flue dust, etc. A comparatively large use is in the manufacture of sodium fluoride which is employed as a wood preservative and as an insecticide.

A special use of fluorspar is in the manufacture of lenses for microscopes and small telescopes. For this purpose only colorless, or very slightly tinged green and yellow varieties are used. The material must be transparent and free from cleavage cracks and must be ¾ inch to 2½ inches in diameter. For this quality from $1 to $10 per lb. are given. In 1918 371 ounces were obtained in Colorado and Kentucky. Before this date, all optical fluorspar was imported. It is now believed that the United States will hereafter be able to maintain its independence of foreign sources.

OCCURRENCE

The mineral occurs in veins, usually with galena, sphalerite and other metallic ores, associated with barite

and calcite, and alongside fault fissures. In Illinois and Kentucky the faults are in Mississippian limestones and sandstones. Thermal water and gases deposited the fluoride in the fault cracks and replaced the rock (where this is limestone) on their sides until veins 16 to 36 feet wide were produced. Often the fault zones are brecciated and the fluorite cements fragments of rocks. When disintegration occurs the fluorite breaks down into fragments forming "gravel" which is collected, washed, and jigged. In this region are dikes of mica peridotite which perhaps indicate the sources from which the gases might have come.[1] In all other places in which it occurs the origin is believed to be similar to that of the fluorite in Illinois and Kentucky.

In Colorado and New Mexico [2] the fluorite is in veins from 3 to 12 feet wide cutting rocks varying in age from pre-Cambrian to Cretaceous. Usually there are associated with the fluorite metalliferous minerals that are mined, but frequently the fluorite forms most of the vein filling. In some places the fluorite is a by-product of metal mining.

Fluorite is known to occur also in Texas, Utah, Arizona, Nevada, Tennessee, Washington and New Hampshire, in each of which States small quantities have been mined.

PRODUCTION AND CONSUMPTION

United States.—The total shipments of the mineral from mines in the United States during 1928 were 140,490 short tons valued at $2,656,554, distributed as follows:

[1] Bain, H. F., "The Fluorspar Deposits of Southern Illinois," U. S. Geol. Sur., *Bull.* 255, 1905.

Ulrich, E. O., and Smith, W. S. T., "The Lead, Zinc and Fluorspar Deposits of Western Kentucky," U. S. Geol. Sur., *Prof. Paper* 36, 1905.

Fohs, F. J., "The Fluorspar, Lead and Zinc Deposits of Western Kentucky," *Econ. Geol.*, Vol. 5, pp. 377–386, 1910.

[2] Johnston, W. D., Jr., "Fluorspar in New Mexico," State Bur. of Mines and Min. Res., *Bull.* 4, 1928.

TABLE LXXX.—FLUORSPAR SHIPPED FROM MINES IN 1928
(In Short Tons)

	Gravel	*Lump*	*Ground*	*Value*
Illinois	56,555	4,066	5,263	$1,154,983
Kentucky	62,528	1,428	5,791	1,426,766
Colorado	1,562	253		
New Mexico and Nevada	1,376	439	1,229	74,805

The imports were 47,183 tons valued at about $408,700. Most of it came from England, Germany, British South Africa and France. Exports were 398 tons valued at $6,586, nearly all to Canada.

The domestic fluorspar was used mainly in basic open-hearth steel works at the rate of 8 lbs. of 85% rock per ton of steel.

TABLE LXXXI.—USES OF DOMESTIC FLUORSPAR IN 1928

	Tons	*Per Cent*	*Value*
Steel	108,064	76.92	$1,641,190
Foundry	3,694	2.63	66,215
Glass and enamel ware	11,212	7.98	338,380
Hydrofluoric acid, etc	17,122	12.19	604,183

Of the imported fluorite 41,380 tons were used in the steel and iron industry, 2,500 tons in making glass and enamel and 3,300 tons in making hydrofluoric acid.

WORLD.—The volume of the world's production of fluorite in 1927 is not known but in 1926 the United States produced nearly 45% of the total.

The largest producers outside the United States are England and Germany. Canada, France, Spain, British South Africa, Italy and Mexico are minor contributors.[3]

Fluorspar is obtained in England as a by-product in the preparation of Carboniferous lead and zinc ores in

[3] U. S. Geol. Sur., *Min. Res., 1916*, Pt. II, p. 317.

Derbyshire and Durham, and in Germany from metalliferous veins in the Harz, Bavaria and Thuringia. In Canada small quantities are mined at Madoc, Ontario, and in the Yale district, British Colombia. The principal Italian mines are in Lombardy. In Switzerland it has recently been discovered in commercial quantities in an abandoned lead mine. In Spain it is a by-product of lead mining.[4] In France excellent fluorspar occurs in the Dept. of Var, at a number of places near Frejus in the Reyran valley, and in comparatively small deposits at St. Laurent-les-Bains, in Ardèche, in Auvergne and in the Vosges Mountains.

CRYOLITE

Cryolite (Na_3AlF_6) is known only at a few places, the most noted being at The Government Mine at Ivigtut in West Greenland,[5] whence all the material of commerce comes. The mineral occurs in a great pegmatite mass in the midst of granite. Through it are scattered quartz, siderite, galena, sphalerite, pyrite, chalcopyrite and wolframite, all of aqueo-igneous origin. Near its borders quartz, feldspar, muscovite, cassiterite and other similar compounds are abundant, all indicating that the aggregate is a deposit from magmatic waters. In some places the pegmatite resembles a graphic granite, composed of intergrowths of microcline and cryolite. The only other known occurrences of the mineral are in the pegmatite of a topaz mine near Miask in Siberia and in a pegmatite near St. Peter's Dome, at the southern base of Pike's Peak, Colorado, but in neither of these places is it in commercial quantities.

[4] For a brief description of the fluorite industry in Spain see *The Mineral Industry During 1926*, New York, Vol. 35, pp. 250–251, 1927.

[5] Ball, S. H., "The Mineral Resources of Greenland," *Econ. Geol.*, Vol. 17, pp. 17–31, 1922, and Gordon, S. G., "Mining Cryolite in Greenland," *Eng. and Min. Jour.-Press*, Vol. 121, pp. 236–240, 1926.

The total shipments of cryolite from Greenland in 1925 aggregated 31,612 metric tons of which 9,239 tons, valued at $690,651, were sent to the United States and the balance to Denmark. In 1928 only 6,906 long tons of the mineral were received in the United States. The value was $529,176.

Cryolite is used to a small extent in the manufacture of alum, but mainly as a flux in the electrolytic preparation of aluminium, in the manufacture of white porcelain glass and in the process of enameling iron.

CHAPTER XXIII

BARITE AND WITHERITE

BARITE

Barite ($BaSO_4$) occurs originally in veins in many places associated with fluorite and metallic sulphides and as a replacement of limestone, but it is found also as a residual product in clays overlying barium-bearing limestones.

The crude ore is sold as lump for the manufacture of lithopone and of barium chemicals, and is ground and refined and sold in this form for a variety of uses.

USES

Ground barite is used as a white pigment, as an inert base in colored paints, as a filler in rubber goods, linoleum, oilcloth, paper, etc. In paints barite does not possess the covering capacity of lead compounds, but on the other hand, it is not discolored by gases. Bleached ground material is used in the paper trade particularly for goods that require a glazed surface like playing cards, etc.

In bleaching, the ore is crushed, treated with H_2SO_4 and again crushed to pass a 200 or 300 mesh screen, and the highest grade material is floated.

Lithopone is a white pigment made from barite. The barite is changed to BaS and mixed with zinc sulphate, when an insoluble precipitate of $BaSO_4$ and ZnS is produced. This is dried, heated red-hot and quenched in water. The mixture is then ground and floated. During the heating a little ZnO is formed which adds to the opacity of the mixture. The pigment is used in making flat paints for interior use.

OCCURRENCE

The principal deposits are in veins cutting limestone (Fig. 122), in irregular masses replacing limestone and as lumps in residual clays above limestone rocks. Metallic sulphides occur with the barite in many places and in others fluorite, quartz, and calcite. Although many geologists regard the mineral as having been dissolved by cold alkaline waters from the neighboring rocks and precipitated in open fissures by solutions of sulphates, the

FIG. 122.—Barite vein in limestone, Cartersville, Ga. (*Courtesy of Geol. Sur. of Georgia.*)

presence of minerals like fluorite, galena, etc., in vein masses is inclining many of the most careful students to consider the material the result of hydrothermal processes.[1]

In Missouri, the mineral occurs in veins cutting Ordovician limestones. It has been thought to have been concentrated by water from the associated limestones. Since, however, it is accompanied by galena,

[1] Hill, J. M., "Geology of the Barytes Deposits of the United States," U. S. Geol. Sur., *Min. Res., 1915*, Pt. II, pp. 166–179, 1917.

and frequently accompanies ores of undoubted hydrothermal origin elsewhere it is believed by Tarr [2] to have been deposited by rising hot water. This method of origin would also account for replacement of limestone by barite elsewhere. In many places there are barite veins similar to those in Missouri that cut schists and

FIG. 123.—Open cut, Tucker Hollow barite mine, Cartersville, Ga. (*Courtesy of Geol. Sur. of Georgia.*)

granites, where the barite cannot have been concentrated from the immediately surrounding rocks.

Most of the barite of Missouri occurs in bowlders in a red residual clay, which results from the weathering of the limestone containing the veins. The bowlders are found scattered irregularly through the clay or in "leads" which follow the loci of old veins. The barite is separated from the galena, chert and other minerals accompanying it by shaking in a box through which water is conducted.

[2] Tarr, W. A., "The Barite Deposits of Missouri," *Econ. Geol.*, Vol. 14, pp. 46–67, 1919, and the "Barite Deposits of Missouri and the Geology of the Barite District," Univ. of Missouri, *Studies*, Vol. 3, No. 1, 1918.

In Georgia [3] (Fig. 123) the occurrences are similar, but recent work in the State suggests that all the deposits were originally of magmatic origin, though most of the production is from residual deposits in clay, many of which have been further concentrated by gravity.

In Kentucky [4] the mineral is associated with fluorite and is obtained largely as a by-product in the mining of this mineral.

In Virginia the mineral occurs as large lenses in limestones and crystalline schists, where it is supposed to replace limestone lenses, and as nodules in the clay above the barite-bearing rocks.[5]

The most important barite deposits abroad are those near Meggen in Westphalia, where a bituminous mass of the sulphate appears to be a replacement of a sheeted pyrite body, in Thuringia where it occurs in veins, and in England and Italy.

Vein deposits of barite in Germany are in the Harz Mountains, in the Thüringer-wald and in the Rhine district. In the first two regions the ore is pure and the deposits large. In England [6] are numerous deposits in the north and near the Welsh border and in Ireland in County Cork. In Canada [7] the principal production is from veins in Nova Scotia; but large veins are known also on the islands in Lake Superior and in the Porcupine district in Northern Ontario.

[3] Hull, J. P. D., "Report on the Barytes Deposits of Georgia," Ga. Geol. Sur., *Bull.* 36, 1920.

[4] Fohs, F. J., "Barytes Deposits of Kentucky," Ky. Geol. Sur., 4th Ser. Vol. 1, pp. 441–588, 1913.

[5] Watson, T. L., and Grasty, J. S., "Barite of the Appalachian States," Amer. Inst. Min. Eng., *Trans.*, Vol. 51, pp. 514–559, 1916, and *Bull.* 98, pp. 345–390, 1915.

[6] Spence, H. S., *Can. Min. Jour.*, Aug. 20, 1926.

[7] Spence, H. S., "Barium and Strontium in Canada," Can. Dept. of Mines, Mines Br., *Bull.* 570, 1922.

PRODUCTION

Barite occurs in a great many parts of the United States but it is produced mainly in Georgia, Missouri, and Tennessee which together yield more than nine-tenths of all mined in this country. California, Nevada and three other States contributed the other tenth.

In 1927 the total sales of crude domestic barite were 254,265 short tons valued at $1,670,878, but 70,274 additional tons were imported by manufacturers. This was used as follows:

	Tons
In the manufacture of ground barytes	73,119
In the manufacture of lithopone	222,791
In the manufacture of barium chemicals	34,280

The production of refined ground barite in the United States in 1927 was 57,658 short tons with a value of $1,166,294 and of lithopone 176,994 short tons with a value of $17,163,620.

The imports were 3,259 tons of ground barite valued at $38,568 and 7,979 tons of lithopone valued at $656,166. Most of the imports were from Germany. Exports of lithopone weighed about 2,110 tons and had a value of $222,585.

In 1927 the world's production of crude barite in metric tons was:

TABLE LXXXII.—WORLD'S PRODUCTION OF BARITE IN 1927
(In Metric Tons)

United States	230,664
Germany	175,000
Great Britain	47,605
France	41,450*
Italy	30,677
Russia	14,389†
Belgium	6,100†
Spain	7,716
Australia	1,916
Austria	1,924
India	1,747

* In 1925. † In 1926.

BARIUM CHEMICALS

The principal barium chemicals at present in use are BaO_2, employed in the manufacture of H_2O_2, and as a bleach for blankets and straw goods.

$BaCO_3$, used chiefly in the ceramic industry, in making case-hardened steel, in the manufacture of optical glass, and of rat poisons and to glaze earthenware.

$BaClO_3$ and $BaNO_3$, used in fire works.

$BaCl_2$ used in purifying table salt, as a mordant, and together with $CaCl_2$ to alloy with lead for use in shrapnel bullets and in thrust washers in automobile differential gears.

$BaSO_4$ precipitated from solutions is known as permanent white, blanc fixe, etc. It is finer and more opaque than ground barite and is used in flat white paints, as an inert base for organic lake pigments and colored lithographic inks, and in the manufacture of highly glazed white paper, oilcloth, rubber goods and putty.

BaS is a laboratory reagent and a starting point for the manufacture of other compounds. It is made by heating barite with coal.

The total tonnage of chemicals made from barite in the United States during 1927 was 23,943 valued at $1,517,994. The imports were valued at $350,465.

WITHERITE

Witherite ($BaCO_3$) is used for many of the same purposes as barite but is much less common. It occurs in veins, often with barite and metallic sulphides. In addition to its use in the manufacture of barium compounds it is employed also as an adulterant for white lead and in the refining of beet sugar.

Commercial deposits of witherite are not known in the United States. The mineral is mined in northwestern England and in Saxony. Imports into the United States during 1927 were 3,300 tons, with a value of $65,821.

CHAPTER XXIV

CELESTITE AND STRONTIANITE

The sources of strontium compounds are the two minerals, celestite ($SrSO_4$) and strontianite ($SrCO_3$). The former occurs in larger quantity, but the latter is more valuable because of the greater ease with which salts can be made from it. Before the war nearly all the strontium compounds used in the United States were imported from Germany, England and Sicily, but during hostilities the domestic strontium industry developed rapidly, the consumption of the raw product doubling between 1914 and 1918. In 1918, however, only 400 tons of the crude ores were produced, mainly in Barstow County, California, and after the close of the war, activity in the mining of strontium minerals languished until at present it has completely ceased. There has been no production of strontium compounds in the United States since 1918. The imports average about 2,700 tons of celestite and strontium salts annually, nearly all from England. Their value in 1927 was $149,383.

Ground celestite is used to some extent as a substitute for barite in the manufacture of a strontium lithopone and as a filler. The principal use of both celestite and strontianite is in the manufacture of strontium salts.[1]

The deposits of strontium ores in the United States are in Arizona, Arkansas, California, Texas, Utah, Washington and around Lake Erie. The material occurs in veins of hydrothermal origin, like barite, and in others

[1] Hill, J. M., "Strontium Ores, Tests, Deposits, Manufacture and Uses," U. S. Geol. Sur., *Min. Res.*, *1916*, Pt. II, pp. 185–195, 1919.

formed by meteoric water leaching strontium salts from the surrounding rocks. It occurs also coating the walls of water courses in dolomitic limestones. The largest deposits are interlayered celestite and strontianite associated with rock salt, gypsum, tuffs and igneous flows, in Tertiary lake beds in California and Arizona, where it was probably precipitated by the evaporation of saline water.[2] But near Aguila, Arizona, a large bed of celestite interstratified with tuffs and flows of Tertiary and Cretaceous age, according to Hewett, appears to be the result of the replacement of tuffaceous material by strontium sulphate from an undetermined source.

In Canada[3] four occurrences of celestite of commercial importance are known in Ontario, the largest being in Bagot, Renfrew County. The celestite which is mixed with barite is found in irregular slab-like masses of radiating or fibrous crystals, from a few inches to three feet in thickness, enclosed in dolomite between steeply dipping limestone walls. A representative sample from a stock pile gave: $SrSO_4$ = 78.50%, $BaSO_4$ = 18.61% and $CaSO_4$ = 0.73%. The total width of the barite-dolomite mixture is about 45 feet, but only about 15 feet is extracted. This contains about 20% of celestite.

The principal producers of strontium compounds are England and Germany.

STRONTIUM SALTS

The principal salts of strontium of economic importance are the bromide, iodide, chloride, hydroxide, nitrate, carbonate, sulphate and salicylate.

The hydroxide and carbonate are used in beet sugar

[2] Knopf, A., "Strontianite Deposits Near Barstow, California," U. S. Geol. Sur., *Bull.* 660, pp. 257–270, 1918.

[3] Spence, H. S., "Barium and Strontium," Can. Dept. of Mines, Mines Br., *Pub.* 570, 1922.

refining, the nitrate in the manufacture of "red-fire," and the other salts mainly in medicine.

In 1924 the production of strontium salts in the United States was 3,061,532 lbs., most of which was made from celestite imported from England. Since that year no statistics are available.

CHAPTER XXV

ASBESTOS

DEFINITION

Asbestos is the name given to various fibrous minerals of which the two most important are amphibole anthophyllite ($(Mg.Fe)SiO_3$) and chrysotile, which is a fibrous serpentine ($H_4Mg_3Si_2O_9$), or a mineral closely related to serpentine. The former is coarse and brittle and its fibers have a low tensile strength. It is therefore not suitable for spinning. Chrysotile fiber is strong and pliable and therefore can be spun.[1] Chrysotile fibers range in length from $^1/_8$ to 6 inches. A third mineral, crocidolite, has recently come into prominence as a substitute for long fiber chrysotile. It is a lavender-blue strongly sodic iron amphibole closely approaching riebeckite in composition. Its fibers are generally shorter than those of chrysotile, but are stronger. Crocidolite is a spinning fiber but is not regarded with as much favor for this purpose as is chrysotile, and consequently does not bring as high a price. Nearly all of it used in commerce comes from South Africa. Amosite[2] is a ferrous iron anthophyllite. Its fibers are long and flexible and therefore can be spun, but they have less tensile strength than chrysotile fibers. It withstands heat and acids better than chrysotile or crocidolite, in this respect resembling anthophyllite. Other substances used as as-

[1] Merrill, G. P., "Notes on Asbestos and Asbestiform Minerals," U. S. Nat. Mus., *Proc.*, Vol. 18, pp. 281–299, 1896.

[2] Peacock, M. A., "The Nature and Origin of the Amphibole-asbestos of South Africa," *Amer. Mineralogist*, Vol. 13, pp. 241–285. 1929.

bestos, especially for chemical filters, are fibrous forms of actinolite and tremolite. They have been spun on a small scale, but are too weak to be satisfactory for this purpose.

ANTHOPHYLLITE.—The anthophyllite fiber occurs in two forms, slip fiber and mass fiber.[3] The slip fiber occurs along planes of slipping, the fibers being parallel to the slipping motion. Slip fiber anthophyllite is employed in making chemical filters for which it is better adapted than chrysotile, because it can withstand a higher temperature without breaking down and because it is not affected by acids or alkalies. It occurs in gneisses and schists especially along fault planes, and can readily be separated only from weathered parts of the rocks, where disintegration has partially freed it from the other rock components.

Mass fiber is a mass of interlocking fibers constituting large bodies of rock. It too can be separated only from weathered material. It is of low grade, brittle and is often discolored by the products of weathering. The best known occurrences[4] are at Sall Mt. and near Hollywood, in Georgia, and at Minneapolis, near Plumtree, in North Carolina. It is reported that 90% of the rock mined at these places finds its way into the finished product. The material is used for paint, fireproof cement, fireproof packing, paper-board filling, etc.

Anthophyllite is being mined also at Kamiah in Idaho and near Pylesville, Maryland. At Pylesville it occurs in the weathered portions of gneissoid schists.

In all 1,165 short tons of anthophyllite fiber valued at $10,950 were produced in the United States during 1925, nearly all of which came from Georgia. Reports for

[3] For a brief description of the varieties of asbestos see E. Sampson, "Asbestos," U. S. Geol. Sur., *Min. Res., 1920,* Pt. II, pp. 311–313, 1923.

[4] Hopkins, O. B., "A Report on the Asbestos, Talc and Soapstone Deposits of Georgia," Ga. Geol. Sur., *Bull.* 29, 1914.

later years do not distinguish between anthophyllite and chrysotile fibers, but it is probable that in 1927 the production of anthophyllite had more than doubled. A part of it came from Plumtree, North Carolina, and a part from Pylesville, Maryland.

Chrysotile.—The chrysotile fiber is mainly cross fiber.[5] It occurs in veins, an inch or two in width, cutting serpentine, and the fibers cross from side to side. This is the most valuable asbestos since it can be spun and woven into high-grade cloth, such as is used in making fire-proof gloves and other garments, safety curtains, etc. It is valued according to the length of its fiber, the best grade three inches long, bringing $2,000 a ton.

Most chrysotile is derived from the alteration of basic igneous rocks by circulating heated waters, but much is formed in magnesian limestone near its contact with sills or intrusive sheets of diabase or other basic rocks.

Chrysotile is sold as crude fiber, just as mined, and mill fiber, which has to be milled to separate it from the serpentine and other materials with which it may be associated. Mill fiber is short. Much of it is used for compressing into asbestos board, etc. The crude fiber is used for spinning. The average price of No. 1 crude fiber in 1927 was about $650 per ton and of mill fiber $46.90 per ton.

Asbestic, which is the waste remaining after separating all fibers, is valued at about $2.05 per ton.

Crocidolite and amosite.—Crocidolite and amosite in their only known commercial occurrences are in cross-fiber veins parallel to the bedding of an ironstone composed essentially of quartz and iron oxides, somewhat similar to the ferruginous cherts of the Lake Superior iron

[5] For a discussion of the origin of cross-fiber veins see S. Taber, "The Origin of Veins of Fibrous Minerals," *Econ. Geol.*, Vol. 19, pp. 475–486, 1924.

ranges. It is believed by Peacock to be a chemical precipitate from sea water. The veins of crocidolite are believed to have been formed by the regional metamorphism of the enclosing rock, which may have had soda-rich layers deposited with the chert. The amosite veins are thought to be due to hydrothermal solutions emanating from an igneous intrusion. The crocidolite is characteristically lavender or blue, and the amosite white or gray or greenish.

ACTINOLITE AND TREMOLITE.—Fibrous actinolite and tremolite occur in slip fiber veins in magnesian rocks, where they have been formed by metamorphic processes. They are used principally in making filters.

USES

The principal use of asbestos is in the manufacture of automobile accessories, such as brake-band linings and clutch facings. It is used also in the form of asbestos cloth for fire-proof curtains, gloves, packings, etc., and in the manufacture of shingles, paper, wall-board, pipe and boiler coverings, mill-board, in roofing and for many purposes in the chemical laboratory.

PRODUCTION—IMPORTS AND EXPORTS

The total production of all asbestos in the United States in 1925 was only about 1,258 short tons valued at $51,700. Of this 93 tons valued at $40,750 was chrysotile. In 1927 the total production of all kinds of asbestos was 2,986 tons, valued at $336,882.

The imports into the United States of all kinds of asbestos during 1927 were 223,693 short tons valued at $8,150,340. Of this 98% came from Canada, constituting about 80% of the production of that country, and most of the rest from British South Africa and Rhodesia.

Additional imports of manufactured asbestos goods were valued at $2,176,827.

The exports were 276 tons of unmanufactured asbestos valued at $48,774.

In spite of its small production of the raw material, the United States is a large exporter of manufactured asbestos products. In 1927 the value of manufactured asbestos exported, exclusive of roofing, was about $2,200,000, and of asbestos roofing about $510,000.

The principal producers in the world are:

TABLE LXXXIII.—WORLD'S PRODUCTION OF ASBESTOS DURING 1927
(In Metric Tons)

Canada	249,273
Rhodesia, Southern	30,097
Russia	21,057
Union of South Africa	20,085
Cyprus	11,079
United States	2,704
Other countries	8,500

OCCURRENCE

UNITED STATES.—The principal production of chrysotile asbestos in the United States is from near Globe, Arizona, and near Roosevelt, a few miles farther west, and from the San Carlos and Apache Indian Reservations.

It has been produced also in Wyoming, near Lander, and in Nevada and Inyo counties in California, and is now being mined in Montana, near the Wyoming State line.[6]

The principal occurrences of anthophyllite have already been mentioned (p. 458).

In Arizona, the cross fiber veins are parallel to the bedding of a limestone, which is intruded by a sill of

[6] Diller, J. S., "The Types, Modes of Occurrence and Important Deposits of Asbestos in the United States," U. S. Geol. Sur., *Bull.* 470, pp. 505–524, 1911.

diabase. The asbestos appears to be near the contact of the limestone and diabase, especially in those portions of the limestone that have been faulted. As elsewhere, it is associated with serpentine. It constitutes about 1% of the rock mined. It is possible that in this case the chrysotile is the result of hydrothermal action of the diabase on the limestone. By this action serpentine is made and in this are asbestos nodules, lenses and veins.[7]

Other countries.—The Canadian asbestos is exclusively the chrysotile variety. It comes from cross-fiber, and to a less extent from slip fiber veins in peridotite in the Province of Quebec, mainly at Thetford (Fig. 124), Blake Lake and Coleraine.[8] The estimated reserves in these deposits are immense. Other large deposits are known near Porcupine, Ontario, from which 172 tons valued at $91,000 were shipped during 1925.

The Russian chrysotile deposits are at Ekaterinburg on the east slope of the Urals and at Irkutsk and Yenisei in Siberia.

The most important asbestos district in Russia, which before the war was a large producer, is northeast of Ekaterinburg. Here there is a deposit 18 miles long and from 20 to 1,200 yards wide, containing about 1,000,000 tons of chrysotile in serpentine. Other occurrences are known to exist in Russia and in Siberia but they have not yet been developed.

The South African deposits are of various kinds. Chrysotile, crocidolite and amosite are the three minerals utilized. In southern Rhodesia both chrysotile and

[7] Bateman, A. M., "An Arizona Asbestos Deposit," *Econ. Geol.*, Vol. 18, pp. 663–683, 1923.

[8] F. Cirkel, *Chrysotile Asbestos, Its Occurrence, Exploitation, Milling and Uses*, 2nd Ed., Mines Branch, Can. Dept. of Mines, No. 69, 1910.

Harvie, Robt., "Asbestos Deposits of the Province of Quebec," *Guide Book No. 2*, Excursions in the Eastern Townships of Quebec and the Eastern part of Ontario. Can. Geol. Sur., 1913.

amphibole asbestos are found at many places, the most important being in the Shabani field in the Belingwe district and in the Meshaba area in the Victoria district. In both areas excellent chrysotile is found in cross-fiber veins. The production during 1927 was 33,172 metric tons, most of which was of chrysotile.

In West Griqualand crocidolite occurs in cross fiber

FIG. 124.—Asbestos mine, Beaver Pit, Thetford, Quebec. (*Courtesy of Mines Br., Can. Dept. of Mines, Ottawa.*)

veins enclosed in thin bedded dark-brown ferruginous shales. The mineral occurs in blue fibers as long as 6 inches.

In the Transvaal and other parts of the Union all three varieties occur. Chrysotile and amosite are both produced in comparatively large amounts. The chrysotile is very high-grade, and the percentage of fiber to rock mined is large. As in Arizona, it occurs in altered dolomite on the contact of diabase. In 1927 the total production of both kinds of asbestos was 17,294 short tons. Of this 12,171 tons were chrysotile. In the Cape Province the

main part of the production is crocidolite, of which 4,839 tons were produced in 1927.

The Cyprus asbestos is chrysotile and anthophyllite, but for some reason at present unknown the chrysotile hardens with depth and becomes brittle, so that only that obtained from the upper 30 or 40 feet is merchantable. In 1927 the production was 11,200 long tons—a large increase over preceding years.

Asbestos is known to occur also in a great number of other countries, notably in Italy, Finland, Austria, Australia, Corsica, China and South America. Some of that in South America is a long, soft, silky crocidolite with fibers 10 inches long; but its quantity is unknown. In China the deposits are said to cover 100 square miles in Chihli Province. They are worked mainly for domestic consumption.[9]

[9] Sampson, E., "Asbestos in 1923," U. S. Geol. Sur., *Min. Res., 1923*, Pt. II, pp. 348–350, 1925.

CHAPTER XXVI

TALC AND SOAPSTONE

ORIGIN

Talc and soapstone ($H_2Mg_3(SiO_3)_4$) are the result of the alteration by dynamic metamorphism of magnesian rocks of all kinds, whether sedimentary, like siliceous dolomite, or igneous, like peridotite; and also of the action of magmatic waters on certain silicates such as tremolite and serpentine. It is found as distinct veins of crystallized material cutting serpentine and marble, as plates and large lenses in these rocks and in schists, and as massive aggregates of finely matted fibers. The aggregates are known as soapstone and the vein and platy material as talc.[1]

USES

Soapstone is sawed and used as linings of acid vats, laundry tubs, etc., as tops of tables and in the manufacture of sinks and electric switch boards. Its value depends upon its softness, infusibility, insolubility in acids and its non-absorbent qualities.

Ground talc is extensively used as a lubricator, as a toilet powder, in the manufacture of gas tips,[2] crayons, refractories, electrical insulation, etc., as a filler in rubber, paper and cloth, in the manufacture of roofing and wall plasters, and as foundry-facing, etc. Crushed talc is used as terrazzo. As talc from different localities differs greatly in physical structure, all talc is not suitable for

[1] Ladoo, R. B., "Talc and Soapstone," U. S. Bur. of Mines, *Bull.* 213, 1923.

[2] Diller, J. S., Fairchild, J. G., and Larsen, E. S., "High Grade Talc for Gas Burners," *Econ. Geol.*, Vol. 15, pp. 665–673, 1920.

all purposes even though they may be classed as high-grade.

OCCURRENCE

Deposits of talc and soapstone are widely distributed, but because of cheapness of the product they have been worked on a commercial scale only in those countries having the highest industrial development.

The principal sources of talc and soapstone in the United States are in a belt on the east side of the Appalachian Mountains from Vermont to Georgia, though a large quantity of very high-grade material that is used in toilet powder and a small quantity of a cheaper grade are mined in California. Talc is known to occur also in a number of other States in which there are metamorphosed rocks. The greater portion is found in lenses in dolomitic marbles.

The talc in Vermont, according to Gillson,[3] occurs in serpentine, in quartz-muscovite-chlorite schist and in quartz-mica-amphibole gneiss, and is the result of the metasomatic alteration of serpentine, amphibole and chlorite through the agency of hot alkaline solutions emanating from a large, buried igneous body. He ascribes a similar origin to all the talc of the Appalachian States though many of the deposits are in marble.

The principal occurrences of talc and soapstone outside the United States are in Canada, Italy, France and Germany. The best talc in the world is mined in Italy, the main producing area being in the Alpine district. The chief Canadian[4] production of talc is from near

[3] Gillson, Jos. L., "Origin of the Vermont Talc Deposits, with a Discussion on the Formation of Talc in General," *Econ. Geol.*, Vol. 22 pp. 246–287, 1927.

[4] Spence, H. S., "Talc and Soapstone in Canada," Can. Dept. of Mines, Mines Br., *Bull.* 583, 1922.

Wilson, M. E., "Talc Deposits of Canada," Can. Dept. of Mines, Geol. Sur., *Econ. Geol. Series*, No. 2, 1926.

Madoc, Hastings County, Ontario, and of soapstone at Robertsonville, Quebec. The German deposits are in the Fichtelgebirge in Bavaria.

Soapstone is obtained mainly from Nelson County, Virginia, where it is quarried, sawed and sold in the form of sinks, tubs, slabs, floor tiles, etc. It is known to occur also in other States, but is not worked elsewhere except on a small scale.

PRODUCTION AND IMPORTS

In 1927 the sales of talc in the United States aggregated 192,316 short tons valued at $2,234,724.

TABLE LXXXIV.—TALC MARKETED IN THE UNITED STATES DURING 1927

Crude		*Manufactured*		*Ground*	
Short Tons	*Value*	*Short Tons*	*Value*	*Short Tons*	*Value*
5,706	$25,365	1,494	$111,650	185,116	$2,097,709

Of these quantities three States produced nearly all the talc—New York, Vermont[5] and California. Most of the soapstone was produced by Virginia, though small quantities were mined in Maryland and North Carolina.

The imports in 1927 were 25,123 short tons of talc with a value of $545,285, mainly from Italy, Canada, and France. A small quantity of high-grade talc was imported also from China. The amount of the exports is not recorded but it is known that 1,627 short tons of "talcum and other toilet powders" with a value of $1,621,068 were shipped abroad during this year.

The world's production of talc and soapstone during 1927, exclusive of soapstone in the United States, was

[5] Jacobs, E. C., "The Talc and Verd Antique Deposits of Vermont," Vermont State Geologist, *10th Rep.*, pp. 232–280, 1915–1916.

about 400,000 metric tons of which the United States produced about 45%, France about 17.5%, Japan and Italy about 8%, and Canada and Austria each about 3½%.

PYROPHYLLITE

A small quantity of the material sent into market as talc is the mineral pyrophyllite ($H_2Al_2(SiO_3)_4$), known in trade as "pyrax," which is the aluminium compound corresponding to talc. It possesses nearly the same physical properties as talc and is used for many of the same purposes. Large deposits[6] are known to occur near Hemp and Glendon, North Carolina. They form lenses lying in a narrow zone within a layer of acid volcanic tuffs, from which they have been formed by metasomatic replacement through the agency of hot ascending waters.

The lenses contain from 50% to 75% of pyrophyllite, which is separated mechanically from the valueless associations. At the present time about 8,000 tons are being mined annually and there is promise of much larger production in the near future, since the deposits are very large.

Pyrophyllite is employed for the same purposes as is talc, especially in the manufacture of crayons and tailors' chalk, and in addition is used in the manufacture of pottery and porcelain.

[6] Stuckey, J. L., "The Pyrophyllite Deposits of the Deep River Region of North Carolina," *Econ. Geol.*, Vol. 20, pp. 442–463, 1925, and "The Pyrophyllite Deposits of North Carolina," N. C. Dept. of Conser. and Develop., *Bull.* 37, 1928.

CHAPTER XXVII

MEERSCHAUM

Meerschaum ($H_4Mg_2Si_3O_{10}$) or β sepiolite is a dense white, or light-colored, earthy aggregate. It is associated with magnesite in nodules in young sedimentary beds in Asia Minor and associated with opal at Thebes, Greece.

Because of its softness and absorbent properties it is used for making pipes, cigarette holders, etc.

Nearly all commercial meerschaum comes from Asia Minor, where it is found as masses which have been weathered from dolomite. These masses, which vary in size from that of an egg to that of a football, lie in sandy beds. They are believed to have been formed by the alteration of serpentine.

In Greece it constitutes pebble-like masses in a "conglomerate," composed of a calcareous clay matrix containing besides the meerschaum fragments of serpentine and hornblende rocks.

Meerschaum is known in this country a little north of Silver City, New Mexico, where it is in veins, lenses and nodules associated with calcite, quartz, chert and clay, but the occurrence has not been developed commercially.[1]

[1] Sterrett, D. B., "Meerschaum in New Mexico," U. S. Geol. Sur., *Bull.* 340, Pt. I, pp. 466–473, 1908.

CHAPTER XXVIII

FERTILIZERS

Fertilizers are employed to supply to the soil certain of its ingredients that are necessary to growing plants, either by replenishing those that have been subtracted from it by crops that have been gathered and removed, or by adding those in which certain soils are deficient. Calcium, potassium, phosphorus and nitrogen are essential to all growing vegetation, but some plants require more than many soils can supply. The deficiency in calcium may be made good by the use of lime, limestone, marl or gypsum. Insufficiency in potash is in some places supplied by glauconite. Lack of phosphorus may be replenished by guano, ground bone, ground phosphate rock, fish wastes, certain slags and manure. Nitrogen is supplied by nitrates, slaughter house refuse, ammonium and other nitrogen compounds.

In many regions it is most convenient to furnish the ingredients necessary for profitable agriculture in the form of manufactured fertilizers, which may contain several of the desired components. While different manufactured fertilizers have different compositions, they all contain potassium, phosphorus and nitrogen. The nitrogen is obtained from saltpeter (p. 299), from ammonium salts obtained as by-products in various manufacturing processes (pp. 171, 177, 178) or by direct extraction from the air. The potassium comes from natural salts (see pp. 278–299), or from the by-products of certain industries, and the phosphorus mainly from rock phosphate, mined for this purpose. In order that the phosphorus in the

rock phosphate may be transformed into an easily soluble form it is treated with sulphuric acid. Consequently, sulphuric acid is a necessity to the fertilizer industry. All the substances necessary to the manufacture of fertilizers except phosphorus and sulphur have already been referred to on earlier pages. Phosphorus is furnished by phosphates and sulphur by the native element and by sulphides and, to a slight extent, by sulphates.

CHAPTER XXIX

PHOSPHATES

Phosphate deposits of commercial importance are guano and phosphate rock. The mineral apatite is also produced to a small extent as a source of phosphoric acid, but is of little economic importance.

GUANO

Guano consists mainly of the droppings of birds and bats intermingled with their skeletons. When dry, and not destroyed by the activity of bacteria, it serves as a fertilizer because of the presence in it of ammonia, lime and phosphoric acid. It is hardly to be considered as a geologic product but it nevertheless is the source of much of the phosphoric acid that occurs in phosphate rock.

Bird guano accumulates wherever birds congregate in large numbers and their droppings are not washed away by the rains. It is found in great abundance on the Pacific coast of South America, particularly on the islands off the coast of Peru, which are famous bird roosts. In some places it forms layers 10 meters thick, being pulverulent on top and solid beneath. An analysis of Peruvian guano gave:

	Per Cent
H_2O and volatile ammonia	15.27
Organic matter and ammonium salts	51.44
Halite and sodium sulphate	5.50
Insoluble siliceous matter	.57
Phosphates of calcium and magnesium	21.11
Calcium and magnesium carbonates	6.11

Where washed by rains the soluble components of the guano are leached from it and pass down into the underlying rock, which, if limestone, is phosphatized. Insoluble phosphates are left as an enamel covering other insoluble components of the original guano, and underlying these is a dense, homogeneous, colored mass of phosphatized rock. On coral islands this phosphatized substance is often found between the branches of coral and is mined.

The unleached guano is employed directly as a fertilizer but the leached, insoluble variety is first transformed into super-phosphate and other soluble forms before using.

There are large deposits of insoluble guano in many of the West Indies but the presence in them of iron and alumina make them undesirable for use in fertilizers.

PHOSPHATE ROCK

Phosphate rock includes not only limestone that has been phosphatized by water leaching guano beds, but also rocks formed by the accumulation of the remains of extinct animals, that have been consolidated by partial solution and reprecipitation. Bones, teeth and other hard parts of animals accumulate in great quantities on the floors of caves and in marshes and great quantities of fish remains, phosphatic mollusk shells, and phosphatic nodules accumulate on some portions of the sea floor.

Bones carry as much as 58% of $Ca_3(PO_4)_2$ and some mollusk shells as much as 55%. Phosphatic nodules, which occur abundantly over the sea bottom in some places, are the result of partial decomposition of bones, teeth and the excrement of sea animals.

Beds of these substances after they are raised and subjected to the action of circulating ground water may be leached of their phosphatic component and may thus furnish material for the phosphatization of limestones,

giving rise to secondary phosphates,[1] which, where they are deposited in cracks in the underlying limestone, are known as cutters (Fig. 125 and 126).

TABLE LXXXV.—ANALYSES OF NODULES FROM DEPTHS OF 150 AND 1,900 FATHOMS

	P_2O_5	CO_2	CaO	Other
150 fathoms.....	19.96	12.05	39.41	28.58
1,900 fathoms.....	23.54	10.64	40.95	24.87

Further, some limestones when originally deposited contained notable quantities of phosphatic shells. When consolidation occurred phosphatic limestones resulted. Later these limestones may have been brought above the sea, and partially dissolved leaving the phosphate behind as a mass of residual nodules, or a compact mass of dense phosphate. In either case the residual material can persist only when preserved by a covering of some impervious substance like clay or by settling into some depression on the surface. In Tennessee the preservation is accomplished by a covering of residual soil; in Tunisia by concentration in hollows. The "cutters" in the Tennessee phosphate fields are solution depressions in the lower portions of phosphatic limestone beds filled by residual phosphatic material produced by the solution of their upper portions.[2]

Beds of phosphate rock made in any one of the ways described may be of any age since the Cambrian.

The deposits of Tennessee, Kentucky and Arkansas are early Paleozoic, those of Wyoming and Montana are

[1] Graham, W. A. P., "Experiments on the Origin of Phosphate Deposits," *Econ. Geol.*, Vol. 20, pp. 319–334, 1925.

[2] Hook, J. S., "The Brown and Blue Phosphate Deposits of South-central Tennessee," *The Resources of Tenn.*, Vol. 4, pp. 51–83, 1914.

Permian, those of South Carolina and Florida are Tertiary, those of Great Britain are Ordovician, those of France, Belgium and Tunisia are Cretaceous and those of Nassau are Devonian.

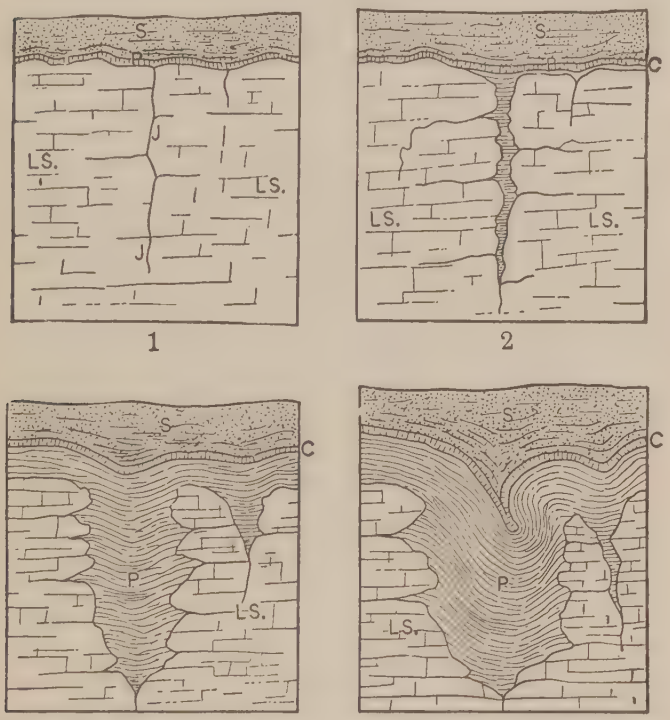


FIG. 125. Sketches showing development of "cutters" of brown phosphate (P) in limestone (LS). C=clay. J=joints. (*After Hook, Miner. Resources of Tenn., Vol. IV, No. 2, 1914.*)

USES

The principal use of phosphate rock at present is as a fertilizer, either in its natural condition, or when combined with potash. Most of it is manufactured into fertilizer, but in 1927 the amount sold for direct use on the soil was 32,957 long tons. It is proposed, however, to employ

some of it in the manufacture of red phosphorus by treating a mixture of low grade rock, low grade coal, sand and shale in an electric furnace. Comparatively small quantities are used in the manufacture of ferrophosphorus and phosphate compounds. About 220,000 long tons were sold for making phosphorus and chemicals, and 25,385 for blast furnace use.

FIG. 126.—Narrow "cutters" of phosphate in limestone. Jackson property, Mt. Pleasant, Tenn. Soft phosphate has been stripped from the top of the limestone. It still fills the cracks extending downward. (*Courtesy of Tenn. Geol. Survey.*)

OCCURRENCE

UNITED STATES.—The principal domestic occurrences of phosphate rock are in Florida, South Carolina, Tennessee, Kentucky and the Western States, Utah, Idaho, Wyoming and Montana. Deposits of minor importance are known to occur also in Kentucky and Arkansas.

Florida.—In Florida[3] the product is classified as hard-rock, land-pebble, river-pebble and soft-rock.

The hard-rock phosphate consists of pebbles and bowlders in a soft matrix of phosphatic sands and clays

[3] Matson, G. C., "The Phosphate Deposits of Florida," U. S. Geol. Sur., *Bull.* 604, 1915.

in pockets resting on an Eocene limestone. The bowlders contain about 85% of $Ca_3(PO_4)_2$ but the marketable product is not more than 15% of the material mined. The total area over which the deposits occur extends with a variable width for 100 miles in the western part of the peninsula. The material is washed and screened and then dried, when it is ready for shipment. Nearly all of the hard-rock phosphate produced is exported.

Land-pebble phosphate is composed of pebbles up to the size of a walnut embedded in a matrix of sand, clay and soft phosphate, forming beds of from a few feet to 25 feet in thickness. The pebbles show evidences of sorting as coarse and fine ones alternate. The beds overlie Oligocene limestone and are covered with sand that averages 15 feet thick. As the beds are regular they are more cheaply mined than the hard-rock phosphate. Their extent is not certainly known because of the cover of sand, but they have been determined to exist in an oval area east of Tampa, Florida, which measures 30 by 40 miles. The phosphate content of the land pebble phosphate ranges from 60% to 75% of $Ca_3(PO_4)_2$.

The river-pebble phosphates are not extensive. They are found along the tributaries of several rivers. The material is usually a mixture of black pebbles less than one inch in diameter, fragments of bones, teeth of sharks and shells of marine organisms in a matrix of sand and sandy clay. They are probably alluvial. The marketed product contains 55% to 65% of $Ca_3(PO_4)_2$.

Soft-rock phosphate forms part of the matrix of hard-rock and land-pebble phosphate. It is largely a mass of secondary phosphates of varying compositions. It is a fine powder or is in soft masses that fall into powder when dried. Much of it is mined with the hard-rock phosphate but is lost in washing. It occurs also in small

pockets in the limestone of the Vicksburg group (Oligocene), and in large bodies at several points near Ocala. It is the most valuable of all the varieties, but is produced only in small quantity.

"The hard-rock phosphate is largely a residual accumulation upon an irregular limestone floor, of Eocene age, of phosphatic debris gathered by the agencies of solution, secondary deposition, and slumping from phosphatic strata of Miocene age. The direction of concentration has been mainly downward, with little lateral transportation, of the phosphate-bearing materials or solutions. The same causes have accentuated the irregularities of the floor on which the phosphate has accumulated. The result is extreme irregularity in thickness and quality of the phosphate bearing mass or matrix."

"The land-pebble is a concentration of phosphate rock by the same processes and from the same sources as the hard rock, with the added features of erosion and redeposition. That is to say, portions of the Miocene phosphate-bearing strata and accumulations of hard rock have both been eroded and redeposited as part of a new group of marine beds of Pliocene age. The floor on which this deposit is laid down is more even and smooth than the floor of the hard-rock deposits. The formation itself is also more evenly distributed through the region in which it occurs."

"In both the hard-rock and pebble fields considerable overburden must be removed, and the matrix includes much clay and sand, together with bowlders of limestone and chert, so that thorough washing is necessary to separate the phosphate from its unprofitable matrix. Some soft phosphate is lost by this process, but the washings from the rock as mined are accumulated in worked-out pits, so that some of this material may be recovered later should the market justify the procedure."

South Carolina.—In South Carolina [4] the phosphate occurs only in a belt 30 miles wide and 50 miles long, surrounding Charleston. Its thickness varies from 8 to 30 inches. It is a ragged mass of honeycombed, soft, chalky brown rock. The river-rock is a mass of loose rounded fragments derived from the land deposits and accumulated on the river bottom.

The material whether excavated by steam shovel or dredged is washed and dried. The average content of shipping phosphate is 58% $Ca_3(PO_4)_2$. Mining has almost ceased in this area because of competition with the higher grade Florida and Tennessee products.

Tennessee.—In Tennessee there are three varieties of phosphate rock recognized, the brown, blue and white rock. They occur in the central and northeastern portions of the State. A large quantity of low-grade rock is also known to occur in the extreme eastern part, but it is not mined.

The brown rock is a residual deposit occurring in horizontal beds of variable thickness, which when they outcrop around a hill are known as collar deposits, and where they underlie broad surfaces as blanket deposits. The material occurs as plates and as a porous mass that rapidly disintegrates into sand. The rock is dug from the surface and crushed, washed and dried. It is sold under a guarantee of from 70% to 80% of $Ca_3(PO_4)_2$.

The blue rock, which is a tough granular rock resembling limestone, is a marine sediment which is mixed with sand, clay and gravel forming beds from a few inches to 3 feet thick. It is mined by underground methods, crushed and dried. Washing is unnecessary. It contains from 30% to 85% $Ca_3(PO_4)_2$.

The white rock is probably a replacement of limestone

[4] Rogers, G. S., "The Phosphate Deposits of South Carolina," U. S. Geol. Sur., *Bull.* 580, pp. 183–220. 1915.

by water percolating through the darker rock which lies above it. It occurs in comparatively small quantities and is not now mined.[5]

Kentucky.—In Kentucky the deposits are brown-rock phosphates forming loose deposits on the surface where they represent residuals 1 to 6 feet thick produced by the weathering of phosphatic limestones.[6]

Arkansas.—In Arkansas[7] phosphate rock occurs in the Ordovician as a bed from 8½ to 10 feet thick. It usually consists of two layers separated by a few inches of manganiferous iron ore. The upper layer is a compact, homogeneous, light-gray rock that runs from 56% to 71% of phosphate. The lower layer is low grade. It has been worked only for local use.

Western States.—The largest development of phosphate rock in the United States is in Utah, Idaho, Wyoming and Montana (Fig. 127).

"The western phosphate rock is much like the Tennessee blue rock in appearance, having a characteristic oölitic texture and a black to brown or grayish color. It is more or less friable, though some beds are hard and dense. It is an original marine deposit, there having been, so far as known, no previous accumulation of residual phosphate, such as was available for rearrangement and redeposition

[5] Hayes, C. W., "Origin and Extent of the Tennessee White Phosphates," U. S. Geol. Sur., *Bull.* 213, pp. 418–423, 1903.

——"The Tennessee Phosphates," U. S. Geol. Sur., *Min. Res.*, 1894 and *16th Ann. Rep.*, Pt. 4, pp. 610–630, 1895.

——"The Tennessee Phosphates," U . S. Geol. Sur., *17th Ann. Rep.*, Pt. 2, pp. 513–550, 1896.

——"A Brief Reconnaissance of the Tennessee Phosphate Fields," U. S. Geol. Sur., *20th Ann. Rep.*, Pt. 6, pp. 633–638, 1899.

[6] Foerste, A. F., "The Phosphate Deposits in the Upper Trenton Limestones of Central Kentucky," Kentucky Geol. Sur., 4th Ser., *Bull.*, pp. 387–439, 1913.

[7] Purdue, A. H., "Developed Phosphate Deposits of Northern Arkansas," U. S. Geol. Sur., *Bull.* 315, pp. 463–473, 1907.

Waggaman, W. H., "A Report on the Natural Phosphates of Tennessee, Kentucky and Arkansas," U. S. Dept. Agric. Bur. Soils, *Bull.* 81, 1912.

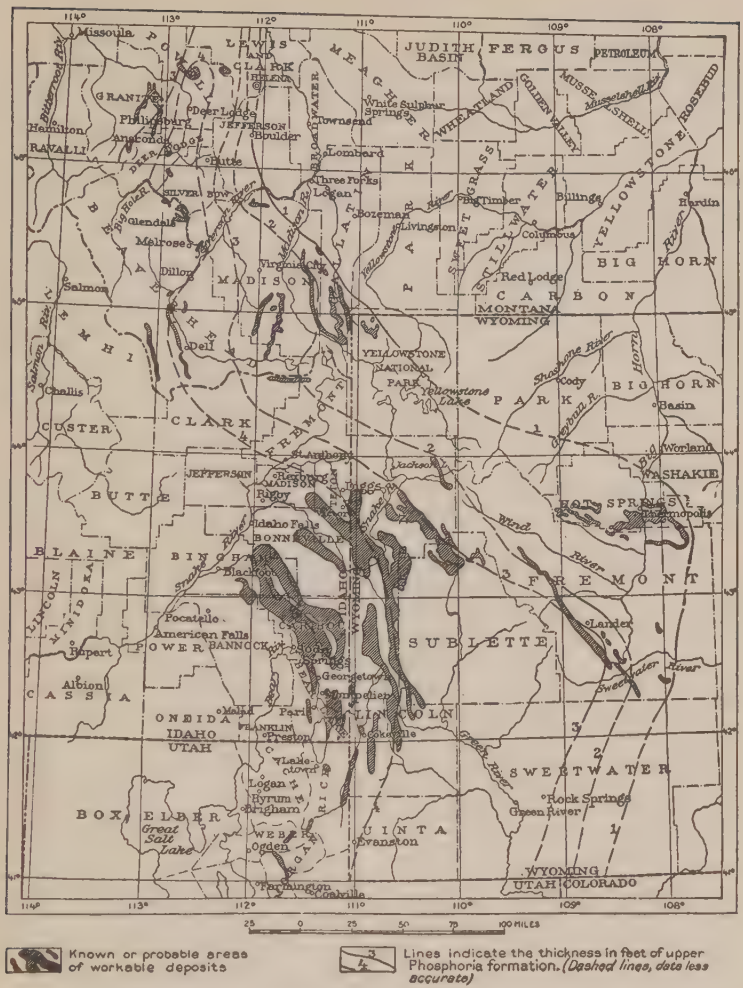


FIG. 127.—Map showing extent of western phosphate fields. (*After G. F. Loughlin & G. R. Mansfield, U. S. Geol. Sur., Bull. 795.*)

when the Tennessee blue phosphate and the Florida land pebble were laid down. It must be mined like coal, by underground methods, but the productive beds are so thick, usually 5 feet or more, that much of the develop-

ment work in a given bed can be carried on in the phosphate rock itself. Thus little waste material need be handled. Moreover, the western rock, like the Tennessee blue rock, needs no washing. The rock thus far mined is relatively dry, but some of the producers run it through a dryer before shipping in order to command a higher price."

The deposits in Utah occur as beds from 6 inches to 13 feet thick in the Upper Mississippian and in the Permian. Their phosphate content ranges from a small quantity to 81.7%. Most of the phosphate is in the Permian series, but in the Woodruff and Crawford Mountains is a bed in Mississippian rocks that is 5 to 6 feet thick and which contains 96,750,000 tons of 70% phosphate.[8]

In Idaho, where the government has reserved 1,015,717 acres of phosphate lands, are 3 workable beds from 3 to 6 feet thick that carry 73%–82.5% of $Ca_3(PO_4)_2$. It is estimated that in the areas studied the main bed which is about 6 feet thick contains 5,200,000,000 tons of phosphate rock carrying 65% of phosphate. Other areas have not been carefully examined, but it is known that the quantity of rock in them is enormous.[9]

The formations here are folded so that the rock must be mined entirely by drifts and slopes.

In Wyoming 1,182,816 acres have been declared as phosphate bearing. In the Canyon of Snake River are 3 beds, 9 feet, 2 feet and 12 feet thick carrying from 20% to 68.5% $Ca_3(PO_4)_2$. Other portions of the State contain 2 or more beds but they are thinner and not so rich.

[8] Schultz, A. R., "A Geologic Reconnaissance of the Uinta Mountains, Northern Utah, with Special Reference to Phosphate," U. S. Geol. Sur., *Bull.* 690, pp. 31–94, 1918.

[9] Schultz, A. R., and Richards, R. W., "A Geologic Reconnaissance in Southeastern Idaho," U. S. Geol. Sur., *Bull.* 530, pp. 267–284, 1913.

Schultz, A. R., "A Geologic Reconnaissance for Phosphate and Coal in Southeastern Idaho and Western Wyoming," U. S. Geol. Sur., *Bull.* 680, 1918.

In Montana there are three distinct fields in which there are beds from 3 to 6 feet thick containing from 60%–72% of $Ca_3(PO_4)_2$. Extimates of two of the fields indicate the existence of at least 183,000,000 tons of high-grade rock.[10]

Reserves.—The total quantity of phosphate rock existing in recognized fields in the United States is not known, but the best estimates indicate an enormous tonnage.

TABLE LXXXVI.—ESTIMATE OF PHOSPHATE ROCK IN THE UNITED STATES, AVAILABLE DECEMBER 31, 1924, IN LONG TONS[11]

Eastern Fields		*Western Fields*	
Arkansas	20,000,000	Idaho	5,169,257,000
Florida	298,704,000	Montana	397,584,000
Kentucky	892,000	Utah	331,973,000
South Carolina	8,941,000	Wyoming	117,594,000
Tennessee	85,300,000		
TOTAL	413,837,000	TOTAL	6,016,408,000
GRAND TOTAL			6,430,245,000

OTHER COUNTRIES.—The chief competitors of American phosphate in Europe are the mines in northern Africa which in 1927 had a combined production of 5,394,000 metric tons. The chief competitors in Australia and Asia are the Pacific Islands. There are important deposits known to exist in British Columbia, Chile, Belgium, Russia, Siberia and smaller ones in France. Palestine, England and New South Wales.

Phosphate rock is known to occur also in the Dutch West Indies, and in the Mesozoic series in French Guiana

[10] Stone, R. W., and Bonine, C. A., "The Elliston Phosphate Field, Mont.," U. S. Geol. Sur., *Bull.* 580, pp. 373–383, 1914.
Pardee, J. T., "The Garrison and Phillipsburg Phosphate Fields, Montana," U. S. Geol. Sur., *Bull.* 640, pp. 195–228, 1917.
Richards, R. W., and Pardee, J. T., "The Melrose Phosphate Field, Montana," U. S. Geol. Sur., *Bull.* 780, pp. 1–32, 1926.

[11] Mansfield, G. R., "Phosphate Rock in 1924," U. S. Geol. Sur., *Min. Res., 1924*, Pt. II, pp. 87–88, 1925.

and Peru but it is not worked to any large extent in any of these countries.

North Africa.—Grabau states that the deposits in North Africa are at an unconformity between Cretaceous and Tertiary formations where there has been concentration of weathering products of the older rocks, together with some secondary alteration.

In Tunisia the Gafsa fields are in the southern part of the country. Here there are several beds of various degrees of richness. Only those in which the rock contains more than 58% of the phosphate are exploited, but these now yield about 2,500,000 tons annually and the yield is increasing rapidly. Since the deposit has been outlined for several hundreds of miles there must be a reserve here of many hundreds of millions of tons. The closest estimate quoted is 1,000,000,000 tons.

These beds extend over into Algeria where they are also worked yielding about 800,000 tons annually. The reserves are estimated at 1,452,000,000 metric tons, grading between 58% and 68% of phosphate.

In Morocco the principal deposits are about 80 miles southeast of Casablanca, in a belt 30 miles long and from 2½ to 17 miles wide. They comprise 3 beds of phosphatic sand, the material of which averages about 75% of the phosphate. Other deposits 40 miles northeast of the one just referred to carry 72% to 75% of the phosphate and a third one near the coast consists of sandy clay 16 feet thick carrying 47% of phosphate.

Although immense quantities of the rock are known to exist in Morocco, the quantity in reserve is not known, except in a general way. It is estimated that there are at least 1,400,000,000 tons of rock containing from 70% to 73% of calcium phosphate.[12]

[12] Mansfield, F. M., "French Mines Active," *Eng. and Min. Jour.-Press*, Vol. 121, p. 619, 1926.

Work in the Morocco fields did not begin until after the war, but once begun the production of phosphate increased rapidly, especially in the Casablanca area.

It is of interest to note that Tunisia, Algeria and Morocco are all under the control of France, so that this country practically dominates the world in the phosphate trade outside the United States. By the Versailles treaty France has come into the possession of the Alsatian potash deposits and thus is now independent of all other nations so far as the possession of fertilizer ingredients is concerned.

Egypt contains extensions of the Algerian deposits, but they are rather thin and irregular. Nevertheless Egypt's production in normal times is about 100,000 tons, all of which comes from fields near the coast of the Red Sea. Other beds independent of the Algerian ones are known to exist also on both sides of the Nile Valley, but there is no estimate of their extent. Egypt's reserve is estimated as 179,000,000 tons.

Oceanic Islands.—The reserves of commercial phosphate in some of the most important of the island deposits are estimated to be as follows:

TABLE LXXXVII.—RESERVES OF PHOSPHATE ROCK ON ISLANDS IN THE PACIFIC AND INDIAN OCEANS

	Tons
Rasa Island near Formosa	2,800,000
Angaur Island	3,500,000
Nauru and Ocean Islands[13]	140,000,000+
Makatea Island	10,000,000
Christmas Island, near Java	2,000,000

On many other islands not mentioned[14] the coral rock has been impregnated with phosphate by water percolat-

[13] Rhone, R. D., "Nauru, the Richest Island in the South Seas," *Nat. Geog. Mag.*, Vol. 40, pp. 559–589, 1921.

[14] Power, F. D., "Phosphate Deposits of the Pacific," *Econ. Geol.*, Vol. 20, pp. 266–281, 1925.

ing through guano deposits and from many of them large quantities of high-grade rock have been shipped. The deposits on Ocean and Nauru islands, 2,200 miles northeast of Sydney, Australia, are believed to be among the richest in the world.

Belgium.—In Belgium the commercially important districts are near Mons and Liège where the phosphate is a concentration product of the weathering of Cretaceous rocks. In the Mons district the phosphate is a chalk containing about 26% of $Ca_3(PO_4)_2$. Near Liège the deposit is a bed 9 feet thick, in which phosphatic nodules are embedded in a matrix of phosphate sand. The material contains only 50% $Ca_3(PO_4)_2$, but it is used locally in direct application to the soil. The production is about 200,000 tons annually.

Russia.—In Russia several districts are important. Of these, one is north, one central and one southern—on the border of Galicia. Only the last has been exploited and this only in a small way, though it is estimated to contain 1,500,000,000 tons of merchantable phosphate rock. The average grade carries 50% phosphate but some of the rock contains as much as 75% $Ca_3(PO_4)_2$.

The phosphate was originally mainly in Silurian deposits as nodules, but these rocks have been broken down and the nodules concentrated in Cretaceous, Jurassic and Tertiary beds.

Recently another deposit has been reported to exist 60 miles from Moscow on the Moscow-Kazan Railway. About 270 acres have already been explored, indicating a reserve of 2,000,000 tons of phosphate rock, but the entire field is much larger and has been estimated to contain a reserve of 63,000,000 tons. The phosphate occurs in two beds with a barren interval of 65 feet between them. The barren ground, however, contains glauconite, and the upper phosphate layer about 25% of the same

mineral, with a content of 10% of K_2O. The exploited ground is reported to contain 320 tons of K_2O to the acre, which, if true, is important, since K_2O and phosphate are the two essential ingredients of fertilizers.

Siberia.—In Siberia also great deposits are known to occur but they are not worked. One of these, bordering on the north end of the Caspian Sea is believed to contain 600,000,000 tons of a rock carrying about 40% $Ca_3(PO_4)_2$. To the east of this another area contains 67,000,000 tons of about 40% rock. All the Siberian rock is low grade and is not now merchantable in international trade.

WORLD RESERVES

The total reserves in the world are estimated by Mansfield [15] as aggregating 10,662,000,000 metric tons of rock with an average grade of 60%, and 6,245,000,000 tons of rock of lower grade.

PRODUCTION

United States.—Before the war the quantity of phosphate rock mined and sold in this country weighed about 3,000,000 long tons and was valued at about $12,000,000. In 1927, the amount sold was 3,017,699 long tons valued at $11,253,352 distributed as shown in table on following page.

The exports of phosphate rock during 1927 were 918,211 long tons valued at $4,731,562. Of this 128,774 tons with a value of $887,732 was high-grade rock and 789,437 tons, with a value of $3,842,830 was land-pebble.

In addition there were also exported 107,507 tons of superphosphates and 14,720 tons of prepared fertilizer

[15] Mansfield, G. R., *Phosphate Deposits of the World.* World conditions as to mining raw materials for the fertilizer industry, pp. 94–107. National Fert. Asso., 1926.

mixtures, with a total value for both of $2,233,048. Germany was the principal importer of high-grade rock, with Belgium and Poland ranking second and third. Japan, Holland, Germany, Italy and Spain imported most of the lower-grade rock.

TABLE LXXXVIII.—PHOSPHATE ROCK SOLD IN THE UNITED STATES IN 1927

	Long Tons	*Value*
Florida:		
Hard rock	131,254	$ 525,016
Land pebble	2,506,166	8,121,146
	2,637,420	$8,646,162
Tennessee:		
Brown and blue rock	481,769	$2,318,785
Idaho	45,260	$ 259,405
Wyoming	6,250	29,000
Total	3,170,699	$11,253,352

The only substances imported that are in direct competition with domestic phosphate rock are apatite, guano, bone dust, bone ash, basic slag and to a very small extent crude phosphates. In 1927 no apatite, and very little basic slag were imported. The imports of crude phosphates were 28,195 tons, valued at $292,871, of guano 23,321 tons with a value of $898,205, and of bone ash and bone dust 46,715 tons, valued at $1,540,897.

OTHER COUNTRIES.—It is impossible to estimate with any close degree of accuracy the world's production of phosphates during 1927, since many countries have not yet published statements of their output.

The largest producers with their production in 1927 were as shown on opposite page.

TABLE LXXXIX.—WORLD'S PRODUCTION OF PHOSPHATES AND PHOSPHATE ROCK IN 1927
(In Metric Tons)

United States	3,221,589
Tunisia	3,075,000
Algeria	919,108
Morocco, French	1,400,000
Ocean and Nauru Islands	633,345
Egypt	279,389
France	253,279 (*a*)
Gilbert and Ellis Islands	192,516 (*b*)
Makatea Island	135,666
Christmas Island	118,553
Curaçao	108,881
Japan	75,386
Angaur Island	61,000
Russia	56,460
Belgium	30,030 (*a*)
Other	60,000

(*a*) In 1926 (*b*) In 1924

The total production of the world for 1927 is estimated at about 10,500,000 tons, of which France and its colonies produced 54%, the United States 30% and the British Empire 9%. Thus, of the fertilizer ingredients produced, Germany is credited with by far the greater portion of the potash and little phosphate, the United States with a large part of the phosphate and little potash and France with more than half of the phosphate and a fairly large part of the potash.

APATITE

Another inorganic source of phosphate is the mineral apatite ($Ca_5(F.Cl)(PO_4)_3$) which occurs as large crystals in pegmatites and as irregular grains associated with magnetite in dikes of iron ore. Apatite also occurs in the rock nelsonite [16] which is a mixture of apatite and ilmenite, found only in Roanoke County, Virginia, and as crystals in some igneous rocks, especially gabbro. The

[16] Watson, T. L., and Taber, S., "Geology of the Titanium and Apatite Deposits of Virginia," Va. Geol. Sur., *Bull.* 3-A, 1913.

rock in which the apatite occurs is mined and crushed and the apatite is separated from the other components by mechanical methods. The phosphate enters the market without further treatment. Apatite has been used in the manufacture of phosphorus, phosphorus alloys and very high-grade superphosphates, but in recent years it has been unable to compete with the cheap phosphate rock and consequently its production has practically ceased.

In the United States the production of apatite is limited to some of the magnetite mines in the Adirondacks where it is sometimes saved as a by-product in the exploitation of iron ores. In Canada it is mined with mica and separated as a by-product.

In Europe it is mined on a small scale in the Province of Càceres, Spain, in Sweden, and between Langesund and Arendal in Norway. In Finland it is produced mainly as a by-product in the iron ore industry.

Within recent years there has been no production of apatite in the United States, and there have been no imports. During the few years before the war the imports from Canada were a few hundred tons annually and from Norway between 700 and 900 tons. In 1927 the only recorded production was 137 tons, in Canada.

WAVELLITE

Wavellite is a hydrous aluminous phosphate, often containing fluorine. It occurs as crusts on the walls of cracks in rocks and lining the walls of cavities in clays, where it has been formed by the action of circulating ground water on aluminous compounds. Large deposits are scarce. The only commercial deposit in the United States is near Mt. Holly Springs,[17] on South Mountain,

[17] Stose, G. W., "Phosphorous Ore at Mount Holly Springs, Pennsylvania," U. S. Geol. Sur., *Bull.* 315, pp. 474–483, 1907.

Pennsylvania, where a bed of white clay under a deposit of manganese and iron ores contains scattered through it small nodules and botryoidal masses of white wavellite. About 25 years ago it was mined and used as a source of phosphorus.

CHAPTER XXX

SULPHUR

The principal uses of sulphur are in the manufacture of sulphuric acid and sulphur dioxide. Since pyrite serves the acid makers as well as sulphur, and since the latter is employed for purposes for which pyrite is not suitable, the use of sulphur for making sulphuric acid is recognized as an economic waste and pressure is therefore being exerted to cause a greater use of pyrite for this purpose.

Sulphur dioxide is used in making paper pulp, as a refrigerating agent, as a bleacher and fumigant and in the manufacture of chemicals.

Sulphur is used in steel pickling, in refining petroleum, in making explosives, as a fertilizer, an insecticide and a fungicide, in vulcanizing rubber, in the manufacture of carbon bisulphide and carbon tetrachloride, and for many other purposes.

ORIGIN

Sulphur is known to be produced by the incomplete oxidation of H_2S that escapes from volcanic vents, where it is probably an emanation from cooling magmas, and of the same gas that escapes from springs, that may have obtained it from magmatic sources or from organic sources. It is also formed when vapor of sulphur in a current of carbon dioxide enters small bodies of water. The sulphur condenses and crystallizes on the walls of openings forming veins if the temperature of the water is at about 110°. The sulphur produced by volcanic gases is frequently referred to as of the solfataric type. It may occur in veins and irregular masses in tuffs, as a

cement in the same rocks, or as veins and impregnations in limestones and in some places as massive replacements of the limestone. In a few places deposits of sulphur of the solfataric type have been worked commercially—as in Utah,[1] Wyoming,[2] Nevada,[3] Colorado[4] and California[5] and in Japan and Mexico.

The greater part of the commercial sulphur now produced has, however, another origin. This is known as the gypsum type, because it is associated so closely with gypsum. Such are the great deposits of Louisiana, Texas and Sicily, which supply the world. With the sulphur and gypsum there are usually present also calcite and limestone, marl and bituminous matter. The deposits in Louisiana and Texas are at the tops of salt domes. The sulphur is in the lower portion of the calcite cap, where it is in contact with the underlying anhydrite and gypsum (see pp. 74–75).

It is believed by many geologists that some of this kind of sulphur has resulted from the reduction of gypsum or anhydrite by the organic matter thus:

1. $CaSO_4 + 2C = CaS + 2CO_2$
2. $CaS + CO_2 + H_2O = CaCO_3 + H_2S$
3. $H_2S + O = H_2O + S$

A recent theory explains the sulphur of Sicily as the result of the action of sulphur bacteria. It is thought that organic matter may have reduced gypsum to CaS

[1] Lee, W. T., "The Cove Creek Sulphur Beds, Utah," U. S. Geol. Sur., *Bull.* 315, pp. 485–489, 1907.

[2] Woodruff, E. G., "Sulphur Deposits at Cody, Wyoming," U. S. Geol. Sur., *Bull.* 340, pp. 451–456, 1908, and "Sulphur Deposits Near Thermopolis, Wyoming," U. S. Geol. Sur., *Bull.* 380, pp. 373–380, 1909.

[3] Adams, G. I., "The Rabbit Hole Sulphur Mines Near Humboldt House, Nevada," U. S. Geol. Sur., *Bull.* 225, p. 497, 1904.

[4] Larsen, E. S., and Hunter, J. F., "Two Sulphur Deposits in Mineral County, Colorado," U. S. Geol. Sur., *Bull.* 530, pp. 363–369, 1913.

[5] Aubury, L. E., "The Structural and Industrial Materials of California," Calif. State Min. Bur., *Bull.* 38, p. 354, 1906.

and perhaps to H_2S (see reactions 1 and 2), but that oxidation was brought about by the bacteria (reaction 3).

An alternative suggestion is that the sulphate was decomposed by one kind of bacteria with the production of H_2S as a waste product. After the production of the hydrogen sulphide by anaërobic bacteria another group of these lowly bodies oxidized the H_2S and secreted drops of sulphur within themselves for slow oxidation to produce the energy necessary for life. In many specimens of these bacteria sulphur occupies 90% of the cell volume of the organism.[6]

At the same time that they secrete the sulphur, these organisms also secrete $CaCO_3$. This neutralizes the sulphuric acid formed by the oxidation of the sulphur, and gypsum results. Thus in many cases gypsum and sulphur must occur together, forming sedimentary deposits upon the death of their hosts. In Sicily where this method of origin has been best worked out it is believed that the gypsum was deposited in lagoons[7] and that in the presence of organic matter the anaërobic bacteria reduced this at temperatures of 25°–30° to the sulphide.

$$1.\quad CaSO_4 + 2C = CaS + 2CO_2$$

In the presence of water this is hydrolyzed

$$2.\quad 2CaS + 2H_2O = Ca(OH)_2 + Ca(SH)_2$$

These reactions can take place only in the presence of some oxidizing organic matter, such perhaps as exists in bituminous shales that are always associated with the sulphur deposits. The CO_2 liberated by the oxidation reacts with the products of equation 2 and produces $CaCO_3$.

$$3.\quad Ca(OH)_2 + Ca(SH)_2 + 2CO_2 = 2CaCO_3 + 2H_2S$$

[6] Stutzer, O., "The Origin of Sulphur Deposits," *Econ. Geol.*, Vol. 7, pp. 732–743, 1912.

[7] Hunt, W. F., "The Origin of the Sulphur Deposits of Sicily," *Econ. Geol.*, Vol. 10, pp. 543–579, 1915.

Thus the sulphur that accumulated upon the death of the sulphur bacteria would be intimately intermingled with limestone, which is the case. The liberated H_2S would soon poison the water and drive the fauna to the surface and finally would destroy the reducing forms (anaërobic bacteria), while the sulphur bacteria might still continue for some time to oxidize the H_2S and store sulphur in their bodies. Moreover, the constantly increasing quantity of H_2S on reaching the surface would become oxidized by contact with the air and furnish additional contributions to the accumulation at the bottom of the basin, and would become disseminated through the limestone.

In many places there is a layer of gypsum above the sulphur deposit. Its presence is explained as being due to the fact that by the continued evaporation of the lagoon water a concentration of NaCl increased until, when it reached about 8%, the anaërobic bacteria were killed and no further reduction could take place.

The origin of the sulphur associated with calcite in the cap rock of the salt domes in Texas and Louisiana may not be the same as that suggested to explain the deposits of Sicilian sulphur, but the processes by which it was formed are not known. It is possible that it resulted by the reduction of gypsum and anhydrite through the agency of bituminous matter, or perhaps of petroleum. Since, however, bacteria have been recognized in oil field waters it is also possible that the reduction may have been caused in part by these organisms in a manner somewhat analogous to that which resulted in the deposition of the Sicilian sulphur.[8]

[8] See Barton, D. C., "The Economic Importance of Salt Domes," Univ. of Texas, *Bull.* 2801, pp. 37–42, 1928.

OCCURRENCE

United States.—The sulphur deposits of the United States are scattered through a dozen States mainly in the West, but the largest mines, producing over 99% of the domestic output are in the salt domes of Louisiana and Texas. Before 1900 when the Louisiana mines began to operate, the importations, principally from Sicily, were about 175,000 tons, but they have now nearly completely ceased. Most of the small quantity now imported is sent from Japan to the Pacific coast cities.

At the small mines in the West the deposits are generally of the solfataric type, but in Louisiana and Texas they are sedimentary, or at any rate are associated with sediments, mainly calcite, gypsum, anhydrite and salt in the salt domes (see pp. 74–77). On top of some domes are sands and gravels with a thickness of a few to several hundred feet. Beneath these are layers of calcite, gypsum, and anhydrite, often 100 feet thick, which is known as the cap rock. This cap covers the salt and in some cases extends a short distance down its flanks. The anhydrite rests directly upon the salt and grades upward into gypsum, which is apparently derived from it by hydration. Above the gypsum is a finely crystalline, a coarsely granular or a cavernous calcite. The sulphur fills small cavities in the calcite near its contact with the anhydrite, and occurs in irregular layers along shear zones in the calcite and as veinlets in both rocks. The sulphur-bearing zones vary in thickness from a few feet up to 250 feet, with a sulphur content that in some places is as high as 40%. To be commercially profitable its content must be at least 10%. The sulphur is reached by wells, is melted by hot steam (sulphur melts at 116° C.) and is forced to the surface by compressed air (the Frasch process). In some places, wells 50 feet apart show no in-

terrelation while in other places those 1,000 feet apart are connected. The quantity of sulphur obtained from individual wells differs—the most productive having yielded 100,000 tons. The crude sulphur is sold with a guarantee of about 99.5% purity.

Not all the salt domes contain sulphur, which seems to be limited almost exclusively to those near the Gulf coast, some of which are immensely profitable. The sulphur dome in Louisiana, which was abandoned in 1924, produced about 10,000,000 barrels of sulphur, with a value of about $155,000,000, or 127,000 tons with a value of over $2,000,000 per acre. At present three domes are being worked, furnishing 83% of the entire world's production.

In Wyoming the sulphur is in irregular masses and veins in limestone and travertine, which in their richest portions contain 30 to 50% of the element. It is believed to have been formed by the action of hot springs. In Utah the sulphur is in cylindrical cores and veins in a rhyolite tuff, where it is still being deposited by fumarolic processes. In Nevada the deposits are shattered and brecciated volcanic rocks containing irregular lumps and veins of sulphur. They are thought to be spring deposits.

Italy.—On the mainland are three sulphur-producing areas all of which are in volcanic districts. Most of the Italian production is from Sicily where the deposits occupy about 5,500 square miles, over which the sulphur layer is distributed in basin-like areas, where the rocks have been faulted and tilted and partially eroded. Pliocene beds of sands, shell breccias and limestones are underlain by upper Miocene gypsum, in the lower portions of which are from 3 to 6 beds of sulphur-bearing rock separated by thin layers of barren clays or shales. The sulphur layers are large lenses of porous limestone carrying from 18% to 50% sulphur, which occurs as incrustations on the

walls of the pores or as thin layers, 1 to 2 mm. thick, interlaminated with the rock.

In view of the fact that the sulphur rock is in lenses that are independent of one another, it is suggested that the deposits must have taken place in restricted basins or lagoons in which the sulphur bacteria worked.

The total production of sulphur in Sicily during 1927 was 231,440 metric tons.

JAPAN.—All the Japanese deposits are of volcanic origin. The sulphur occurs in clays in the beds of ancient crater-lakes and in muds that have been ejected from volcanic vents.

CHILE.—The sulphur deposits in Chile, which are large and numerous, are also of volcanic origin. The sulphur is in beds and veins on the flanks and in the craters of old volcanoes, but the deposits are so high in the mountain that they are unprofitable to work.

OTHER COUNTRIES.—Sulphur is known to occur in Spain, Switzerland, Poland, Greece, Mexico, France, China, Peru, Turkey and Austria but in none of these countries except Spain has there been any considerable production.

PRODUCTION

The quantity of sulphur produced by the mines in the United States during 1928 was 1,981,875 long tons of crude sulphur valued at $37,500,000, nearly all of which came from the Coastal Plain of Texas.

Imports were 4,787 tons of sulphur and sulphur ore valued at $21,320, and exports 685,051 tons valued at $14,345,075. In addition 20,000 tons of refined sulphur and flowers of sulphur, valued at $706,766, were also exported. The exports went to nearly all countries bordering the oceans, the greater part being taken by Germany, Canada, France, Australia, Holland, England and New Zealand.

The largest producing countries outside the United States are Italy, Spain, Japan, and Chile. In 1927 production was as follows:

TABLE XC.—WORLD PRODUCTION OF SULPHUR IN 1927

(In Metric Tons)

United States	2,106,644 (*a*)
Italy	215,280
Spain	15,000
Japan	66,619
Chile	10,000
TOTAL FOR WORLD	2,413,000

(*a*) Long tons.

RESERVES

The reserves of sulphur in the world are estimated by Mansfield [9] at between 30 and 37 million tons, exclusive of the reserves in Texas and Louisiana. The reserves of these two States are thought by Barton [10] to be in the neighborhood of 140,000,000 tons.

If these estimates are approximately correct, though they seem large, the total amount of sulphur known to exist in the world will supply the demand for only 90 years. It is probable, however, that sulphur will be found in Texas and Louisiana salt domes not yet explored, and perhaps in some of those in Europe and elsewhere.

[9] Mansfield, G. R., "Report of Paper Read at Williamstown, Mass.," *Eng. and Min. Jour.*, Vol. 123, pp. 567–570, 1927.

[10] Barton, D. C., "The Economic Importance of Salt Domes," Univ. of Texas, *Bull.* 2801, pp. 44–47, 1928.

CHAPTER XXXI

PYRITE

Pyrite, in the trade, includes the minerals pyrite, marcasite and pyrrhotite. The first two are dimorphs with the composition FeS_2 (S = 53.4%) and the last is Fe_7S_8 — $Fe_{11}S_{12}$ (S = 40%±). Neither of these minerals as mined is pure. The pyrite often contains chalcopyrite (FeCuS), and when this is in sufficient quantity to raise the content of the ore to 3% or 4% of copper, it is used as a source of this metal rather than as a source of sulphur. The pyrite furnished to the trade contains between 38% and 43% of sulphur. Lead, zinc, arsenic, antimony and selenium are objectionable constituents and even if a small quantity of either is present the ore is penalized.

As many of the metallic ores are sulphides, much sulphur might be saved at smelters, and made into sulphuric acid. Since, however, most smelters are a long distance from the districts in which sulphuric acid is used, and transportation costs are high, most of the sulphur fumes produced by them are allowed to escape. At present only about 1,500,000 tons of acid, valued at $18,000,000, are saved annually as a by-product, and nearly all of this is produced at eastern smelters.

It is thought that with the development of the phosphate rock in the northern Rocky Mountain States, the demand for sulphuric acid in these States will increase and the saving of the sulphur by the mountain smelters may become profitable.

Pyrite and the sulphides classed with it are common, but the material is so cheap that deposits to be of value must be large, fairly pure and situated near markets.

ORIGIN

The principal productive areas of the United States are in the Southern Appalachians, where the minerals occur in lenses associated with schists; in the Middle Western States where it is in bands and nodules associated with coal beds; in the Rocky Mountains where it occurs in veins with other sulphides, and in the Pacific States where it is in veins and lenses in igneous rocks. There are immense reserves in the West but they are too far from market to be of value.

The vein material is of magmatic origin. The lenses are probably replacements of crushed material or of limestone lenses in schists that have been brought about by magmatic vapors. The "pyrite" from the coal beds is frequently marcasite. It is probably a secondary product formed in part by reactions between the decomposing organic matter and the iron of the neighboring rocks and concentrated by circulating water into concretions. In the trade these are known as "coal brasses," and are not favorably considered, partly because the coal adhering to them makes dark acid and partly because marcasite decomposes rapidly, heating and catching fire, or else oxidizing to sulphuric acid on the dump, where the acid cannot be saved.

In some portions of Europe large deposits of pyrite have separated by direct segregation from igneous magmas.

PRODUCTION

United States.—In the United States there are over 50 mines in 14 or 15 States that can be called upon to furnish sulphur ore when the demand increases, and the method of occurrence of the ore in nearly all mines in the same district is similar. In 1917 when pyrite was in fair

demand the distribution of the production was as follows:

	Tons	*Value*
The Appalachian district	258,066	$1,955,464
The eastern Mississippi Valley district	39,463	129,318
The western Mississippi Valley district	49,316	67,452
The Pacific Coast	115,817	333,501

Of this, 104,311 was crude ore and 358,351 was concentrate.

In 1928 the output was only 182,049 long tons, valued at $605,459. California and Virginia furnished the entire tonnage.

Imports were 457,123 tons with a value of $1,135,463, nearly all of which came from Spain. A small quantity (about 60,000 tons) was imported from Canada.

World.—The world's production of pyrite in 1928 was about 7,200,000 metric tons, or about 750,000 tons more than the previous maximum production, which was in 1912.

Table XCI.—World's Production of Pyrite in 1918 and 1928
(In Metric Tons)

	1918	1928
Canada	373,418	59,655
France	260,310	202,084
Germany	817,883	350,430 (*a*)
Greece	12,433	94,270
Italy	482,060	558,390
Japan	105,757	506,089 (*a*)
Norway	338,849	617,044 (*a*)
Portugal	111,851	210,487 (*b*)
Spain	1,597,716	3,618,691
Sweden	141,181	69,239 (*a*)
Cyprus	.....	243,913
United States	421,922	184,971
Total	4,743,448	7,200,000±

(*a*) In 1927. (*b*) In 1926.

USE

Pyrite is used almost exclusively in the manufacture of sulphuric acid. In 1917 about 1,450,000 tons were consumed for this purpose, of which about 480,000 tons were of domestic origin and 970,000 tons were of foreign origin. In recent years, however, sulphur has displaced much of the pyrite.

After the extraction of the sulphur from the sulphides the residues left are treated for copper or other metal, or are sintered and sold as iron ore to blast furnaces under the name "blue-billy." Small quantities of the thoroughly roasted residues are used also in paints.

A small quantity of pyrite crystals amounting to 6,500 lbs. for which $5,000 was received were used in radio sets.

During the war a thorough examination of the pyrite resources of the country was made and the preliminary results of this investigation are given in the Mineral Resources for 1917, showing that the reserve of pyrite is enormous and that in time of need the United States can supply the domestic demand without difficulty, but since most of the deposits are comparatively small the cost of the ore will be high.

OCCURRENCE

United States.—At the present time the domestic production of pyrite is from California and Virginia. New York, Ohio and, in some years, Wisconsin and Georgia produce minor quantities though the reserves in each State are large.

Near Mineral, Virginia, both pyrite and pyrrhotite are mined. The pyritic ore contains small quantities of sphalerite, chalcopyrite, galena and magnetite. The mine waters are treated for copper and this is saved as a

by-product. The ore is in great lenses conforming rather closely with the schists in which they lie,—the largest being 700 feet by 80 feet and from 1,200 feet to 1,800 feet deep. The pyrite is supposed to be a replacement of limestone, as the surrounding rocks are old metamorphosed sediments containing streaks of very impure limestone with calcium silicates.

The pyrrhotite is mined from the Great Gossan Lead, which is a mass of limonite covering the ground underlain by the sulphide for a distance of 18 miles with a width of 100 feet. For a time this was worked for copper and later for iron, until the covering, which is 100 feet thick, was penetrated and the sulphide brought to view. The ore is at least 700 feet deep and at least 35 feet wide. It consists of pyrrhotite mixed with mica, talc, and a little hornblende and quartz. It is concentrated to contain about 35% sulphur. In all probability it is a distinct vein.[1]

In Georgia[2] pyrite occurs both in veins and in lenses. The veins are from 4 to 25 feet wide, 200–700 feet long and 400, or more, feet deep. The ore is concentrated on a 4:3 basis. In other places the pyrite is a series of thin lenses extending in vein-like masses for 1,100–2,000 feet, in which the pyrite is mixed with quartz and chlorite. This must be concentrated on a 3:1 basis.

In California the pyrite forms a great lens 600–700 feet long, 50 by 200 feet wide and more than 100 feet deep in a granite at the point where mined, but there are also other lenses of such size that under favorable conditions this State alone could furnish all the pyrite now needed for all industries in this country.[3] Most of the sulphide

[1] Watson, T. L., *Mineral Resources of Virginia.* The Virginia Jamestown Exposition Commission, Lynchburg, Va., pp. 190–209, 1907.

[2] Shearer, H. K., and Hull, J. P. D., "A Preliminary Report on a Part of the Pyrite Deposits of Georgia," Ga. Geol. Sur., *Bull.* 33, 1918.

[3] Mace, C. H., "Genesis of Leona Heights Ore Deposit," *Min. and Eng. World,* Vol. 35, p. 1320, 1911.

contains also copper and other metals that are recovered as by-products after the sulphur is driven off by roasting.

The deposits in New York which may become of considerable importance in the future and which have yielded a large aggregate tonnage in the past are in St. Lawrence County. They are lenticular impregnations in old crystalline limestones and schists.[4] The ore contains from 20% to 35% of sulphur which was raised by concentration to about 50%. Pyrite is also obtained as a by-product in zinc-ore concentration near Edwards in the same county.

In Illinois[5] and the East Central West pyrite and marcasite occur with coal.

Spain.—The largest deposits of pyrite at present known are at Rio Tinto, Spain, but other large deposits occur also in Portugal.

The deposits at the Rio Tinto Mines have been mined since Phœnician time and still produce a large portion of the world's supply of the mineral. There are 50 or more lenses from 1,200 to 6,500 feet long, 750 feet wide and from 500 to 1,800 feet deep, occupying a belt 100 miles long by about 15 miles wide. The lenses occur in slates or porphyries or between them. The ore is a mixture of chalcopyrite, pyrite and minor amounts of other sulphides from which copper, lead, silver and gold are obtained. Alongside the lenses are abundant evidences of hydrothermal alteration and in consequence the ores are believed to be replacements of crush zones by magmatic waters and vapors.[6] The reserves in the district are estimated

[4] Smyth, C. H., "On the Genesis of the Pyrite Deposits of St. Lawrence County," N. Y. State Mus., *Bull.* 158, pp. 143–182, 1912.

Newland, D. H., "Pyrite," New York State Mus., *Bull.* 223–224, pp. 209–218, 1919.

[5] Holbrook, E. A., "The Utilization of Pyrite Occurring in Illinois Bituminous Coal," Ill. Univ. Eng. Exper. Sta., *Circ.* No. 5, Vol. 14, No. 51, Aug. 20, 1917.

[6] Finlayson, A. M., "The Pyritic Deposits of Huelva, Spain," *Econ. Geol.*, Vol. V, pp. 357–372 and 403–437, 1910.

Bateman, A. M., "Ore Deposits of the Rio Tinto (Huelva) District,

at 272,730,795 tons certain and 147,561,838 tons probable, or enough to supply the world for 60 years.

Canada.—The deposits in Canada[7] are like those in the Southern Appalachians and in addition there are a few that are unquestionably replacements of limestones. There are also large deposits that are supposed to be separations from a magma, either as segregations or as replacements of the constituents of a norite by "a very liquid melt charged with sulphides and developed by differentiation" in a deep magma reservoir.[8] Among these is the pyrrhotite in the Sudbury district, but this deposit is worked mainly for nickel and copper. Other large deposits are in Hastings County, Ontario, and in the Eastern Townships of Quebec.

Other countries.—In Norway and in Bavaria much of the pyrite may have been injected as a liquid sulphide at high temperatures. Flat ore lenses prevail, but the mineral occurs also as veins in metamorphic rocks. In some deposits the sulphide is probably a magmatic segregation. In northern Norway one deposit has been described as being a massive lath-shaped intrusive in schist. It is said to measure 75 feet in thickness, and 3,000 feet in width, and is of unknown length. Concentrations of copper at its top and along its sides indicate that the ore is a mixture of pyrite and chalcopyrite.

Other deposits, some of them large, occur in Tasmania, Italy, France, Greece, Hungary and Japan. Small deposits are widely scattered and many countries have been producers on a small scale.

Spain," *Econ. Geol.*, Vol. 22, pp. 569–614, 1927, and Douglas, G. V., "Note on the Origin of the Rio Tinto Ore Bodies," *Ibid.*, Vol. 22, pp. 742–744, 1927.

[7] Wilson, A. W. G., "Pyrites in Canada, Its Occurrence, Exploitation, Dressing and Uses," Can. Dept. Mines, Mines Br., *Pub.* 167, 1912.

[8] Cf. Lindgren, W., *Mineral Deposits*, 3rd Ed., New York, p. 902, 1928.

SULPHURIC ACID

The total production of sulphuric acid[9] in the United States during 1918, estimated on the basis of 50° Bé., i.e., an acid containing 62.18% H_2SO_4, was 7,450,000 short tons, valued at about $90,000,000. This was used approximately as follows:

TABLE XCII.—DISTRIBUTION OF THE USE OF SULPHURIC ACID IN THE INDUSTRIES, ESTIMATED AS OF 1918
(In Long Tons)

Explosives	2,700,000	Metallurgical and storage batteries	292,000
Fertilizers	2,130,000	Paints, glue, etc	104,000
Oil refineries	671,000	Fabrics, textiles, etc	100,000
Chemicals	740,000	Miscellaneous	73,000
Steel pickling and galvanizing	700,000		

In 1914, when 3,800,000 tons of acid were produced only 2.6% was made from sulphur. In 1918 this percentage was increased to 48%. The sources of the sulphur used for this purpose in the two years was as follows:

TABLE XCIII.—PERCENTAGES OF ACID PRODUCED IN THE UNITED STATES FROM DIFFERENT SOURCES IN 1914 AND 1918

	1914		1918	
	Tons of 50° Acid	*Per Cent*	*Tons of 50° Acid*	*Per Cent*
From sulphur	100,000	2.6	3,580,000	48.0
From pyrite:				
Spanish	1,900,000	50.0	570,000	7.6
Canadian	300,000	7.9	550,000	7.5
Domestic	600,000	15.8	950,000	12.7
From roasting zinc ores	500,000	13.2	1,200,000	16.1
From waste gases at copper smelters	400,000	10.5	600,000	8.1

[9] Wells, A. E., and Fogg. D. E., "The Manufacture of Sulphuric Acid in the United States," U. S. Bur. Mines, *Bull.* 184, 1920.

After the war the use of sulphuric acid in the manufacture of explosives fell rapidly and consequently the quantity of sulphuric acid made also decreased. In 1920 the production fell to the equivalent of 5,602,403 short tons of 50° Bé. acid, valued at $59,292,406 and 502,970 tons of strong acids valued at $10,624,049. In this year 688,372 long tons of native sulphur, 765,462 long tons of pyrite, 654,252 long tons of copper sulphides and 425,655 long tons of zinc sulphides furnished the sulphur. The zinc smelters produced 731,702 short tons of acid valued at $10,119,256, and the copper smelters 497,806 tons of acid valued at $3,497,819.

In 1926 the production of acid was about 7,035,000 tons of 50° Bé. grade valued at about $50,000,000. About two-thirds was made from sulphur, one-sixth from pyrite and one-sixth from the fumes of smelters. In addition 27,969 short tons with a value of $337,634 were imported. The exports were 4,612 tons of high-grade acid valued at $174,423.

The distribution in the use of the acid during 1928 was very different from that in 1918, due mainly to the cessation of the war and to the increase in amount of petroleum refined.

TABLE XCIV.—DISTRIBUTION OF THE USE OF SULPHURIC ACID IN THE INDUSTRIES DURING 1926
(In Short Tons)

Fertilizers	2,300,000	Steel pickling	695,000
Oil refineries	1,350,000	Explosives	170,000
Chemicals	745,000	Textiles	130,000
Coal Products	700,000	Paints, glue, etc	210,000
Metallurgical	600,000	Miscellaneous	285,000

Other sources of sulphur employed in the manufacture of sulphuric acid in addition to pyrite, sulphur and the fumes of smelters are barite and gypsum. In Germany

the sulphur gases produced as by-products in the manufacture of barium chemicals from barite, and in the manufacture of Portland cement from a mixture of gypsum, coal and clay, slag or sand, are treated like the sulphur fumes of smelters and transformed into sulphuric acid.

The United States leads in the production of the acid, and is followed in order by France, Germany and Great Britain, as will be seen from the following table:

TABLE XCV.—SULPHURIC ACID PRODUCTION OF THE WORLD IN 1925, IN TERMS OF 50° BÉ. ACID
(In 1,000 Metric Tons)

United States	6,300	Belgium	740
France	1,840	Poland and Danzig	320
Germany	1,800	Spain	230
Great Britain	1,300	Denmark	175
Italy	1,075	Holland and Sweden	290

CHAPTER XXXII

MINERAL PIGMENTS AND MINERAL FILLERS

PIGMENTS

Most of the mineral pigments used in paints are manufactured from materials mined principally for other uses. Some of them are minerals that are refined and then simply ground and mixed with oils. Others are made directly from minerals or mineral residues by some simple treatment and others are compounds that consist of salts made by chemical reactions.

Among the more important of these three classes are:

1. Ground gypsum, known as terra alba or mineral white
   Ground graphite, forming metal-protective black paint
   Chalk, known as whiting
   Ground asbestos, forming fire-proof paint
   Ground hematite and ground roasted pyrite, forming dark red paint
   Ground black, yellow and red shale and clay, for use in mortar colors and fillers in oil cloth, linoleum, etc.
   Ocher, a clay permeated by iron compounds
      Red ocher, in which the coloring matter is hematite
      Yellow ocher, in which the coloring matter is limonite
   Umber, a mixture of iron and aluminous silicates with manganese oxides. Raw umber is drab, and burnt umber is reddish brown
   Sienna, like umber, but with less manganese and consequently lighter in color
   Ground siderite, forming a light brown paint
2. Zinc white is zinc oxide (ZnO)
   White lead is hydrated basic lead carbonate ($(PbO)_3(CO_3)_2 + H_2O$)
   Red lead is lead oxide (Pb_3O_4)

Vermilion is mercuric sulphide (HgS), or basic lead chromate ($Pb_2(OH)_2CrO_4$)
Cadmium yellow is cadmium sulphide (CdS)
Chrome yellow is lead chromate ($PbCrO_4$)

3. Lithopone is a white pigment made from barite
Cobalt blue is a complex cobalt aluminate
Ultramarine is an artificial lapis lazuli

The best ochers come from France, the best sienna from Italy, the best umber from Ceylon, and excellent red hematite from Spain. The United States produces annually about 22,000 tons of ocher, umber, and sienna and of other natural mineral pigments about 55,000 tons.

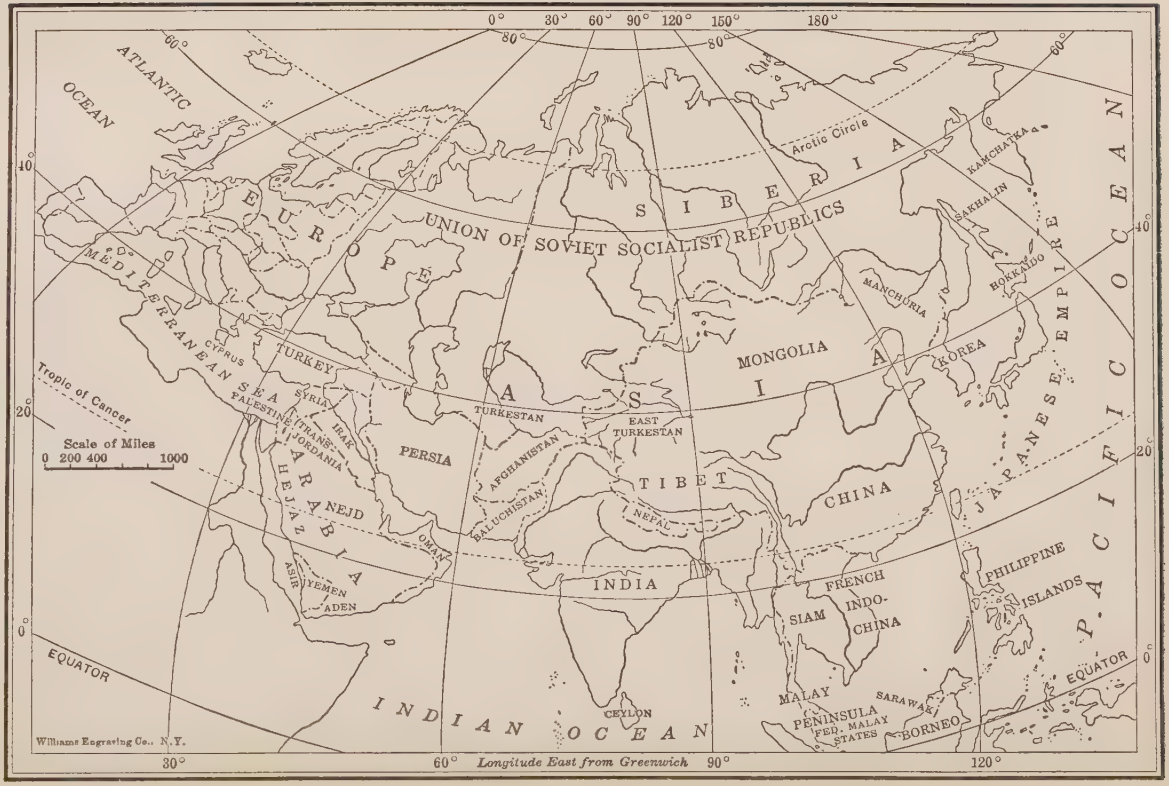
FILLERS

Mineral fillers are finely ground mineral materials that are introduced into many industrial products to add body to the finished product or to give it opacity or some other desirable property. They are used particularly in paper, rubber, paint, linoleum, oil cloth, fertilizers, putty, soap and some textiles. Some of them are described in previous pages. Among the most common are clay, anhydrite, apatite, asbestos, talc, serpentine, barite, bentonite, calcite, celestite, chalk, infusorial earth, dolomite, feldspar, flint, fuller's earth, gypsum, graphite, iron oxides, limestone, magnesite, marble, mica, ocher, umber, pumice, pumicite, pyrophyllite, rottenstone, sand, shale, quartz, soapstone, sulphur, tripoli and whiting.

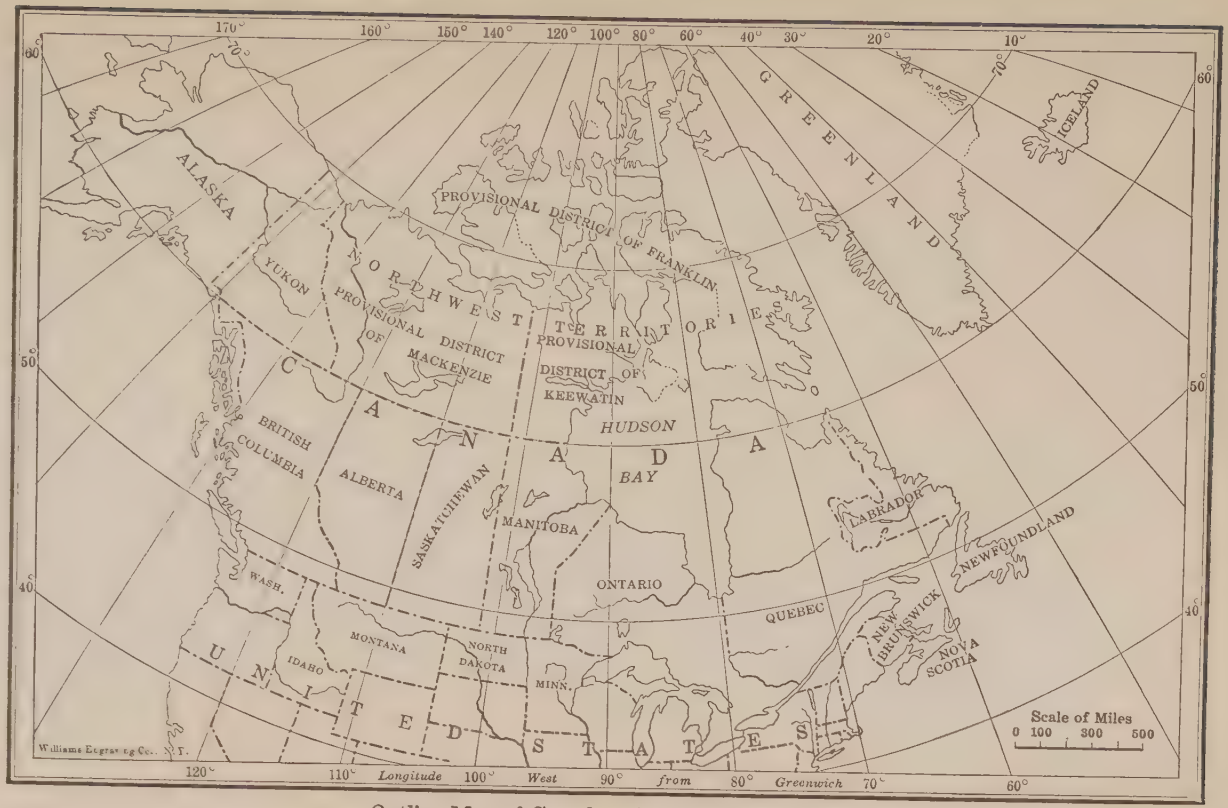
Outline Map of Europe

Outline Map of Australia and Neighboring Islands

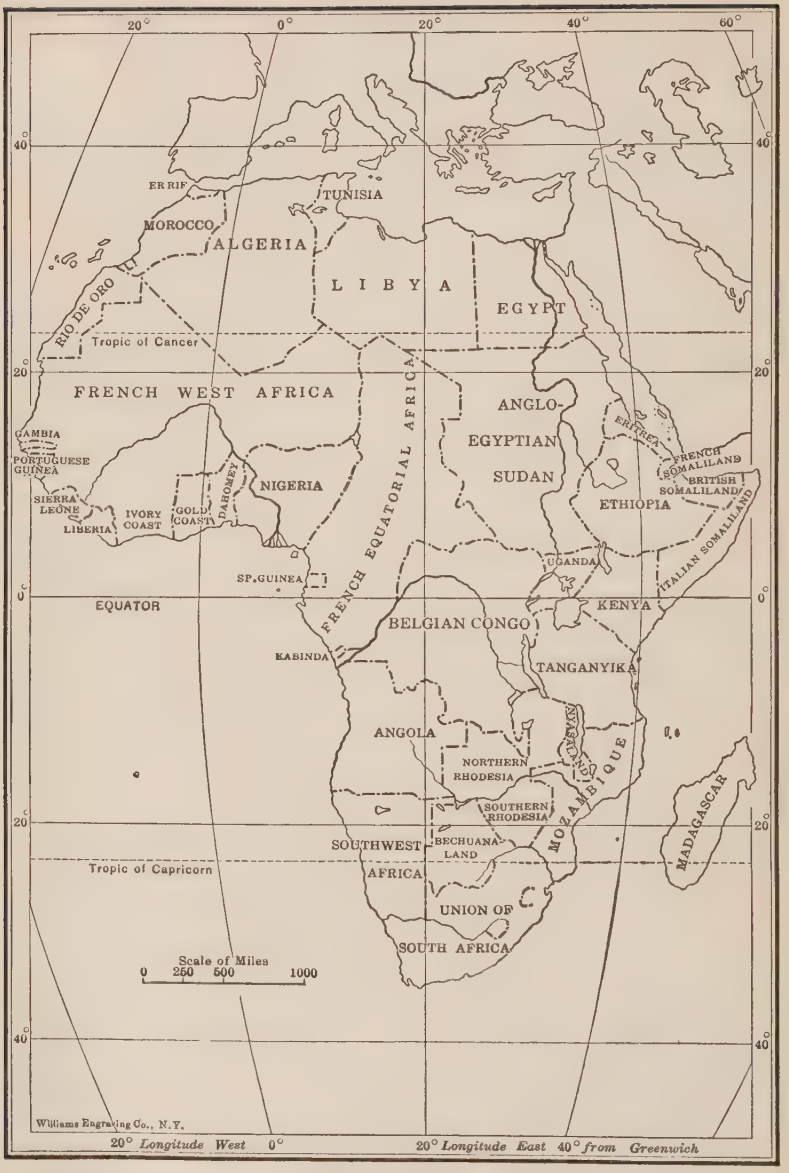
Outline Map of South America



Outline Map of Asia



Outline Map of Canada, Alaska, Greenland, etc.



Outline Map of Africa

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